Understanding hydrological ecosystem services produced by the Indo-Gangetic basin and selected mountain catchments in the Himalayas

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Understanding hydrological ecosystem services produced by the Indo-Gangetic basin and selected mountain catchments in the Himalayas

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Abstract

This research examines major hydrological ecosystem services produced by the Indo-Gangetic Basin and selected mountain catchments in the Himalayas. Key focus is given to quantity and quality related hydrological attributes that underpin many hydrological ecosystem services. A quantitative assessment of changes in these hydrological attributes in the context of plausible land use and cover change scenarios is crucial for policy making processes to sustain important hydrological benefits. Using a process-based advanced hydrological modelling tool, i.e. WaterWorld (www.policysupport.org/waterworld), the research estimates baseline hydrological fluxes and compares them with the same fluxes under future plausible land use scenarios. The research has used globally available datasets of hydro-climatic, bio-physical, and environmental properties available in the web-based 'SimTerra' database. Fieldwork was also conducted for selected catchments to improve the quality of datasets for modelling and to integrate the local understanding of watershed conservation and hydrological ecosystem services into the research.

The vast expanses of croplands in the lowland areas are consuming the majority of available freshwater. The research also highlights the important role of crops carrying hydrological ecosystem services (in embedded form as 'Virtual Water') to local and distant consumers. Projected cropland growth uses additional water which will affect water availability for other hydrological ESs. In this situation, the agricultural and water resources related policies should be focused on the efficient use of freshwater resources. In addition, water consumed in crop production processes should be better integrated in hydrological ecosystem services research.

Both Protected Area and human dominated catchments in the middle-mountainous region of the Himalayas are supplying valuable hydrological ecosystem services to downstream users. Conservation efforts of upland people have had a positive impact on water quantity and quality related attributes. Although the conservation intervention has improved the upland forest cover and increased annual evapotranspiration, the bigger increase in fog inputs at the same time has resulted a marginally increase of annual water availability in the downstream. Thus, a positive contribution of fog water inputs is a new phenomenon for the mountainous region. Upland communities' voluntary role in watershed management is clearly reflected through their participation in various conservation activities. Since conservation practices are essential in improving hydrological ecosystem services, a payment for the ecosystem services programme might help them to achieve their goal.

Abbreviations and Acronyms

AET	Actual Evapotranspiration
BIWMP	Bagmati Integrated Watershed Management Programme
CGIAR	Consultative Group on International Agricultural Research
CI	Conservation International
CIESIN	Centre for International Earth Science Information Network
CPWF	Challenge Programme on Water and Food
CWI	Cloud Water Interception
DDC	District Development Committee
DEM	Digital Elevation Model
DNPWC	Department of National Park and Wildlife Conservation
DSCWM	Department of Soil Conservation and Watershed Management
ESs	Ecosystem Services
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FIESTA	Fog Interception for the Enhancement of Stream Flow in Tropical Area
GIS	Geographical Information System
GWh	Gigawatt hours
HEP	Hydro-electric Power
HMGN	His Majesty's Government of Nepal
hrs	Hours
HydroSHEDS	Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales
IBA	Important Bird Area
ICIMOD	International Centre for Integrated Mountain Development
ICRAF	International Centre for Research in Agroforestry
IFAD	International Fund for Agricultural Development
IGB	Indo-Gangetic Basin
IUCN	International Union for Nature Conservation
IWMI	International Water Management Institute
KUKL	Kathmandu Upathyaka Khanepani Limited
LAI	Leaf Area Index
LDD	Local Drainage Direction
LUCC	Land Use and Cover Change
Masl	Metre above sea level

MEA	Millennium Ecosystem Assessment
MLD	Million Litres per Day
Mm^3	Million Cubic meters
MODIS	MODerate Resolution Imaging Spectroradiometer
MW	Megawatt
NEA	Nepal Electricity Authority
NGO	Non-Government Organization
NRs	Nepalese Rupees
NTNC	National Trust for Nature Conservation
PA	Protected Area
PES	Payment for Ecosystem Services
PET	Potential Evapotranspiration
PSS	Policy Support System
RUPES	Rewarding Upland Poor for Environmental Services
SCWM	Soil Conservation and Watershed Management
SNNP	Shivapuri Nagarjun National Park
SRTM	Shuttle Radar Topographic Mission
TESSA	Toolkit for Ecosystem Service Site-based Assessment
TRMM	Tropical Rainfall Measuring Mission
US$	United States Dollar
VCF	Vegetation Continuous Field
VDC	Village Development Committee
WCD	World Commission on Dams
WCS	Wildlife Conservation Society
WDPA	World Database on Protected Areas
WWAP	World Water Assessment Programme
WWF	World Wide Fund for Nature

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Chapter 1 Introduction and Aims

1.1 The Indo-Gangetic Basin and available freshwater resources

The Indo-Gangetic Basin (IGB) is a contiguous basin comprised of the Indus and Ganges river systems. It covers an approximate area of 2.20 million km^2, representing all of Nepal and a significant part of India, Pakistan and Bangladesh. It also covers a small part of China (Tibet) and Afghanistan. The basin can be divided into three major physiographic regions: the high mountains (the Himalayas), the mid-mountainous region and the lowland plains (Fig 1.1, below). Both rivers originate in the high mountainous region of the Himalayas and incorporate several tributaries downstream. The name of the Himalayas itself literally means 'the abode of snow' and it has the largest snow and permafrost covered areas in the world outside the Polar Regions (ICIMOD, 2008 and Eriksson et al., 2009).

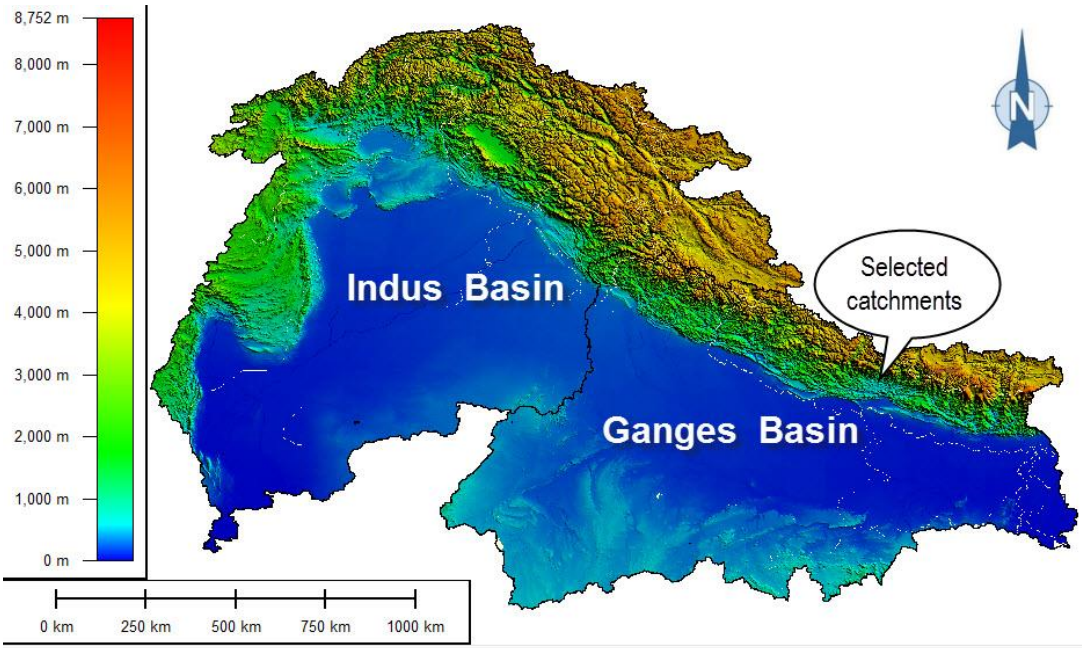


Figure 1-1: An overview of HydroSHEDS DEM of the IGB catchments showing the location of selected local catchments in the Himalayas (Lehner et al., 2008)

In the IGB catchments, freshwater resources are retained in three different major forms that include the cryosphere (snow, ice, glacial lakes and permafrost deposits), the biosphere and lithosphere (soil moisture, groundwater, aquifers, natural water bodies and wetlands), and the constructed systems (canals, lakes and reservoirs) (Vaidya, 2009). Groundwater is also a major freshwater source that is now extensively used in lowland flood plain areas to fulfil the increased water demand. As a result, the unsustainable use of groundwater is already reaching its tipping point in the majority of the lowland Indus Basin as well as the north-western parts of the Ganges Basin (Shah, 2007).

The IGB is one of the most densely populated basins on earth with more than 750 million people. Freshwater resources are a lifeline to millions of people living in both the upstream and downstream areas of the IGB. The majority of the population reside in rural areas and mostly depend on agriculturally based subsistence livelihoods. The available freshwater resources are exploited across the region to fulfil human demands, traditionally in agriculture, livestock and domestic water supply, and recently in industrial uses and hydro-electric power (HEP) generation. Various factors including the change in population dynamics and economic expansion have drastically increased water consumption in the region. Among other factors, population growth and life style changes have triggered the increased withdrawal of all available resources. Cropland expansion and intensification is still continuing across the basin and has exerted additional pressures on both surface and groundwater sources.

The high mountains provide important intra- and inter-annual water storage facilities to the entire basin. Rainfall that occurs during the monsoon period is a major source of freshwater that also helps in recharging aquifers and groundwater. In the western parts of the basin, much of the runoff comes from snow and ice melt and less from monsoon rainfall (Eastham et al., 2010b). The high altitude wetlands of the Himalayas play a vital role in water storage and regulation of the hydrological cycle. In the lower regions, aquifers and groundwater storage are also major freshwater stores. In the Indus basin, when the mean rainfall rate is lower, several months may receive almost 100% of river discharge from rainfall and snowmelt in the Himalayas (Viviroli et al., 2007). Such a harsh hydro-climatic situation has a direct impact on many freshwater related services, for example, the Indus Irrigation Scheme in Pakistan depends on approximately 50% of its water originating from snowmelt and glacial water from the western Himalayas, the Karakorum and the eastern Hindu-Kush mountains (Winiger et al., 2005).

In the IGB region, the agricultural sector is the largest consumer of freshwater resources with some 75-90% of total freshwater consumption (Nellemann and Kaltenborn, 2009). Cropland consumes freshwater in the form of green water (soil moisture) and blue water (surface and groundwater), both of which are supported by precipitation. However, due to the advancement of better technology to extract groundwater (or deep fossil water), water demand is being fulfilled by withdrawal of such water sources. Cereal production is traditionally a key agricultural output that covers the majority of the cropland area in the region. By 2050, the demand for freshwater supply will increase by 70-80% to meet the needs of an increased human population, cereal demand for human consumption and animal feed, and to adapt with progressive climatic change (Nellemann and Kaltenborn, 2009). Such increasing demands could be met through intensive use of available sources such as diverting rivers, storing rain water and extracting more groundwater. Greater efficiency of freshwater use will also be a central issue in the coming decades. High slope gradients and the perennial nature of snow-fed mountain rivers are regarded as favourable conditions for HEP generation. A recent estimation from the Himalayan region shows that about 150,000 MW of additional renewable energy (from HEP projects) will be added in the next 20 years (Dharmadhikary, 2008).

The use of freshwater is continually increasing across the IGB regional countries in order to satisfy the increased water demand from cropland, industrial growth and a growing human population. This trend may have also prompted to find out appropriate trade-offs among different services, for example, while expanding cropland in the IGB floodplains, there is less availability of water for other hydrological ecosystem services (ESs) such as water supply to cities, fisheries, floods and droughts regulating, and river navigation. The future projection of water demand is clearly related to increased population density both in the mountainous and lowland floodplains. The problem posed by the growing demand for hydrological ESs is compounded by increasingly serious degradation in the capability of ecosystems to provide these services. The combination of ever-growing demands being placed on increasingly degraded ecosystems seriously diminishes the prospects for sustainable development.

1.2 Rationale for the research

Although the importance of hydrological ESs are well recognized, especially since the Millennium Ecosystem Assessment, there are still huge research gaps in terms of quantitative assessment of the amount and the scale of ESs delivery (Brauman et al., 2007). It is also vital to improve the understanding of the distribution of key hydrological ESs at different geographical scales. Considering these research gaps, this study is designed to develop a robust knowledge of hydrological ESs produced in the IGB catchment at different spatial scales. Local catchments are also selected for a detailed understanding of hydrological ESs produced by protected and non-protected areas. Moreover, we focus on the need to achieve such assessment in areas with a paucity of local measurement and monitoring assessment.

The main rationale for this research is based on the quest for quantitative knowledge of hydrological ESs in the context of land use change scenarios, their spatial distribution and resulting policy implications. Modelling of hydrological processes is one of the best ways to quantify hydrological ESs in different spatial scales. Such knowledge strongly supports policy and decision making processes for better water resource management and watershed conservation sustainability.

1.2.1 Quantitative knowledge

Quantitative knowledge of freshwater resources is essential for a better understanding of hydrological ESs. Due to the dynamic nature of hydrological systems, it is extremely difficult to measure freshwater services accurately at scales beyond a certain point. Major hydrological inputs such as rainfall, fog input and snow and ice melt are constantly changing both spatially and temporally. In this situation, spatial quantitative modelling is a useful scientific method for identifying and assessing hydrological ESs at policy relevant scales.

Traditionally, hydrological ESs of catchments are considered as positive externalities or public goods that can be freely available to downstream areas (Postel and Thompson, 2005). The value of freshwater related services has been changed due to the vast scale of human appropriation of freshwater resources (MA, 2005a and Brauman et al., 2007). Crop production consumes a huge amount of freshwater, and brings virtual water services (embedded in crops) to actual beneficiaries located at proximal and distant locations (see, Chapagain and Hoekstra, 2008; Siebert and Döll, 2010; Aldaya et al., 2010, Allan 2011 and Mulligan et al. 2013). Similarly, HEP projects also supply hydrological ES in the form of energy to people within and beyond river basins. Domestic water supply (for drinking water and sanitation) to rural and urban areas across the basin is also an important freshwater service. Industrial use of freshwater is ever increasing and underpins economic growth. Freshwater demands in most of these sectors are constantly increasing. Despite the clear evidence of the direct benefits from hydrological ecosystem services, there is still a lack of well-established scientific knowledge for quantitative assessment of the impacts of land use and land management on the provision of those services.

Although hydrological ESs are well recognized in ecosystem services research, there are still many research gaps in terms of their production, service delivery and identifying (and integrating) actual beneficiaries into PES markets (Brauman et al., 2007). Modelling of freshwater ecosystem services can improve understanding of those services, their current state, their geographical availability and any future trends (based on actual and projected scenarios) of services (see, Alcamo et al., 2005 and Nelson and Daily, 2010). Since there are many competing demands from different water use sectors, quantitative assessment could provide information for alternative solutions for the better management of freshwater resources.

Recently, the water availability and the use of some of the major river basin systems (including the IGB) were assessed (see, Mulligan et al., 2011 and Eastham et al., 2010a&b). Such assessments are useful in understanding freshwater availability, their uses and challenges at the basin scale. However, there is still a profound gap of quantitative assessment of water related ecosystem services at regional administrative scales. Water related policies in the IGB catchments are decided at the administrative region scale (such as local, regional and country levels), and respective authorities need details of the availability of water and its spatial distribution for better decision making. In addition, PES markets, which have a different set of goals including conservation, sustainability and poverty alleviation at local scales, clearly need a science-based quantitative assessment of available hydrological ecosystem services, their use and distribution and the geographical location of actual beneficiaries. Considering the need for quantitative assessment, this research is designed to focus on the modelling of freshwater services provided by the IGB catchments at different scales. So, the outcomes can expand the scientific knowledge of freshwater related services and such findings could be useful for the decision making process.

Modelling crop ET related services is an innovative approach in this research. The research has assessed the balance between gained transpiration services that support crop production and the loss of runoff services. Another novel approach in this research is the integration of distant beneficiaries into ecosystem services research. Some hydrological ESs have regional and global significance, for example; agricultural products which are exported outside the catchment - thus they embed a considerable amount of hydrological ESs which are provided to distant consumers. Similarly, water supply systems and HEP projects also provide hydrological ESs to distant consumers. Currently, those beneficiaries are not adequately addressed in the ESs research. We try to better understand these issues so the research may help us to integrate them into ESs market mechanisms in the future.

1.2.2 Geographical distribution of ESs provisions and actual beneficiaries

Most of the hydrological provisioning services (except water embedded in some exportable freshwater services such as crops, fisheries and forest products) are consumed within the originating basin. Agriculture and livestock based activities are the primary livelihood means for millions of rural dwellers in the IGB. Lower-mountainous regions and downstream plains are heavily populated and people are mostly relying on subsistence-based agricultural livelihoods. More than 80% of the Ganges Plain is now covered by cropland (Ramankutty et al., 2008), and cropland uses almost 90% of freshwater in the Indo-Gangetic basin in regard to human usage (Nellemann and Kaltenborn, 2009). As a result, agricultural products are carrying a huge amount of water services (embedded in production) to actual beneficiaries as it is indicated by the relatively new concept of virtual water (Allan, 1997; Allan, 2003; Hoekstra and Hung, 2005 and Allan 2011). Thus, water related ESs are distributed to actual consumers located not only within the originating basin but also to a wider geographical scale.

The value of ecosystem services relies on their use and the distribution of beneficiaries at different geographical scales, i.e. local, regional and global. This makes the quantitative assessment of certain services more complex, for example, water services of agricultural goods and HEP energy are distributed not only within the catchment but also far beyond it. Those distant beneficiaries are not fully integrated in ESs research. Payment for Ecosystem Services (PES) programmes mostly deal with directly benefitting individuals or those beneficiaries located within the proximity of the services. Understanding indirect beneficiaries and their geographical distribution is very important to the long-term success of PES markets (Landell-Mills and Porras, 2002). Spatial modelling of hydrological ESs and the location of actual beneficiaries will improve the knowledge of ecosystem services, their flow pattern and the distribution of all types of beneficiaries.

1.2.3 Policy implications

The concept of ecosystem services is now an important one for the linking of functioning ecosystems to human wellbeing (Fisher et al., 2009). A series of PES-based programmes were designed in the last decade - mostly on an ad-hoc basis - to maintain ecosystem services and reward service providers; so improved services could be delivered to beneficiaries (see, Landell-Mills and Porras, 2002; RUPES, 2003; Wunder 2005; Farley and Costanza 2010 and Stanton et al., 2010). Payments for watershed services are widely practiced around the world due to their direct benefits in managing upstream areas for downstream beneficiaries (see, Van Noordwijk, 2005; Pires, 2004; Postel and Thompson, 2005; Porras et al., 2008 and Huang et al. 2009). However, the success of many PES programmes is contextual and the links to the poverty alleviation agenda are sometimes tenuous (Huang et al., 2009). The resource managers and their beneficiaries are also not fully integrated in existing resource management and financial mechanisms. Due to a lack of appropriate methods for ESs quantification and valuation, many ESs are still poorly understood and hindered in terms of their proper integration into landscape planning, management and design (Chan et al., 2006; Daily et al., 2009 and De Groot et al. 2010). Thus, robust scientific knowledge of ESs in terms of their amount, location and their distribution is essential in improving relevant policy measures (Brauman et al., 2007 and Daily et al, 2009). Such work will ultimately help to capture the growing potential of future PES markets.

Hydrological ESs are also closely interrelated with local and regional policies of other ecosystem services, conservation activities and economic growth. Systematic assessment of hydrological ESs provide a way for policy/decision making bodies to understand the impacts and trade-offs of land use change (such as expansion of cropland or forested areas) and can illuminate the gains and losses to different beneficiaries at different spatial and temporal scales (Brauman et al., 2007). Despite the rapid expansion of PES programmes in recent years, these programmes are still reluctant to address some beneficiaries such as distant consumers. There is a huge gap both in terms of scientific basis and policy mechanism which needs to be addressed in order to incorporate these issues into decision making processes. This research will help to fill some of these research gaps while dealing with hydrological ESs of selected catchments.

Moreover, my own research experience in Rewarding Upland Poor for Environmental Services (RUPES) - a pioneering PES project implemented in the Kulekhani watershed area and my MPhil thesis work entitled '*Environmental services and equitable benefit sharing in the Hindu Kush-Himalayan region*' - has given me some deeper insights into how quantitative modelling of water services can improve the knowledge of hydrological ESs and support water resources based policies at local and regional scales.

1.3 The selection of research sites

The research is designed to assess hydrological ESs at two major spatial scales - the regional scale by crop ET assessment of the IGB catchments and the local scale by selected mountain catchments for their hydrological ESs provisions of drinking water supply and the HEP generation. For the local scale hydrological assessment, the research has selected a protected area (PA) and a human dominated mountain catchment in the middle-mountainous region. The rationale for the selection of research sites is illustrated below.

The selection of IGB catchments is based on the region's large scale croplands where water resources are extensively used in crop production. IGB is also one of the most densely populated basins, and agriculture is the main source of livelihood for hundreds of millions of rural individuals. Regional countries also have higher rates of population growth and this may trigger cropland expansion and intensification processes in the lowland areas. Such a situation would lead to direct pressure on water availability for not only crop production but also other hydrological ESs. Thus, a detailed and process based crop ET modelling of the IGB catchments has a greater significance in hydrological research of the region.

The selection of the Shivapuri Nagarjun National Park (SNNP) represents a well-established mountain catchment in terms of its water resources and watershed management policies. The park is a major source of freshwater supply in the Kathmandu valley (KUKL, 2009). In addition, a small hydropower plant located at the Sundarijal sub-catchment is generating HEP energy to the wider public. In the PA catchment, past conservation efforts were directly supported by the government and various international donors. Such support may help to improve the condition of ESs. Although the catchment is managed under the national park guidelines, upland communities voluntarily contribute in various conservation activities but they do not receive any direct incentive for their positive actions. In the long term, the park might also require financial support to sustain conservation activities as pressures on government finances have an effect on the conservation balance sheet.

Considering the services provided by the catchment, the recently emerged PES mechanism could be a useful choice to protect and maintain watershed ecosystem services whilst diversifying upstream livelihoods (Landell-Mills and Porras, 2002; Wunder, 2005 and Pagiola, 2008). A detailed study of available and realized hydrological ESs is crucial while developing any payment mechanisms. Potential beneficiaries located in the downstream areas may need further information about the actual amount of ESs increased due to upland people's voluntary contribution to management. Therefore, a detailed understanding of hydrological ESs in the context of plausible land use change scenarios is crucial for better water resources management policies.

Similarly, the research has selected the Kulekhani catchment to assess HEP related hydrological ESs in a densely populated mountainous region. The catchment has also witnessed various conservation interventions in order to improve the conditions of hydrological services. However, many watershed management programmes – often with international support – are now becoming unsustainable in the region because of the lack of appropriate follow-up programmes and sustained funding (Rao and Pant, 2001). There is a lack of a sustainable mechanism for the continuation of such watershed management programmes. Since the initiation of Payment for Ecosystem Services (PES), an opportunity has arisen to continue and expand these watershed conservation programmes. The PES mechanism could play a vital role in the region where upland people are contributing in producing improved hydrological ESs to actual beneficiaries located in downstream areas. A detailed assessment of hydrological ESs produced by the selected catchment is hugely important for sustainable watershed management activities in the region.

Despite a huge significance of hydrological ESs provided by mountain catchments, they are mostly considered as a part of the water infrastructure or a cost-effective mechanism for sustaining downstream water flow (Emerton and Bos, 2004). There is no reward for upland communities for their voluntary role in watershed conservation as well as secured supply of hydrological ESs to downstream beneficiaries (van Noordwijk, 2005). Hydrological ESs maintained by these areas (with the support of upland communities) have been mostly ignored in policy and decision making processes. Thus, the detailed assessment of hydrological ESs of the selected catchments would support water resources management strategies in the region.

1.4 Aims and objectives

The overall aim of this research is **to improve the understanding of key hydrological ESs produced by the IGB catchments at different geographical scales through a process-based hydrological modelling and analysis of hydrological key attributes (fluxes)**. To understand the hydrological ESs, we must first need to know the amount and types of hydrological fluxes. Major hydrological fluxes quantified here are wind-driven rainfall, fog inputs, actual evapotranspiration and the resulting water balance. At the IGB scale, we model cropland AET at the administrative region level, and at the local catchment scale, we assess hydrological ESs and associated key attributes of selected catchments in the middle-mountainous region of the Himalayas. The research also assesses the impacts of plausible land use and cover change (LUCC) impacts (i.e. due to cropland expansion or conservation interventions) on key hydrological attributes of IGB administrative regions and two selected catchments. The study has the following specific objectives:

a) **To model crop ET and its potential impact on future water availability at the IGB administrative region scale**

   The research assesses the water consumption in cropland evapotranspiration processes and models how a future plausible cropland cover scenario for the year 2050 will affect water availability across the basin. Since the water resources are allocated at an administrative regional level, the policy implications of this research are important for the sustainable use of water resources. The objective is addressed in Chapter 4 as a peer reviewed published paper.

b) **To assess provisioning services associated with water supply of a Protected Area catchment**

   The research has selected the Shivapuri-Nagarjun National Park (SNNP), an important catchment in the region which provides nearly 50% of the drinking water supply to Kathmandu City. A small hydro-electric power project is also supported by a sub-catchment. We concentrate on the amount of water generated from the catchment and the impact of modelled plausible land use changes on water provision (quantity) and erosion/sedimentation levels (quality). The stated objective is discussed in Chapter 5.

c) **To assess hydrological ESs and the long-term prospect of Payment for Ecosystem Services (PES) in a human dominated catchment**

For a human dominated catchment, the research has chosen the Kulekhani catchment, also located in the middle-mountainous region where available water resources are collected in a human made reservoir and used in HEP production in the downstream areas. For this catchment, we also assessed an already implemented PES scheme and how such schemes will support hydrological ESs in the long-term. The research has addressed this objective in Chapter 6.

The study findings from the selected catchments provide a glimpse of major hydrological ESs of the region. We also assess the potential role of fog inputs in selected mountain catchments. Modelling plausible land use change scenarios under the influence of human interventions is crucial in understanding the likely future changes on water availability and potential impacts on hydrological ESs.

1.5 The theoretical framework for this research

1.5.1 Catchment hydrology and hydrological ESs provisions

Catchments[1] receive freshwater resources in the form of rainfall, fog inputs, snow and ice melt, and then drain via surface runoff and aquifers into numerous tributaries and on to the main river channel. At the catchment scale, the quantity, quality and timing of freshwater resources are directly affected by local and upstream hydro-climatic features, topography, vegetation cover, geological condition, land use and human interventions. A huge amount of water is lost to a catchment in evapotranspiration (ET) from croplands, forests and other vegetation, lakes, rivers and bare grounds. The water remaining after ET is called the water balance which is available for various hydrological ESs provisions. The water budget model for a catchment can be represented as shown in fig. 1.2 below:

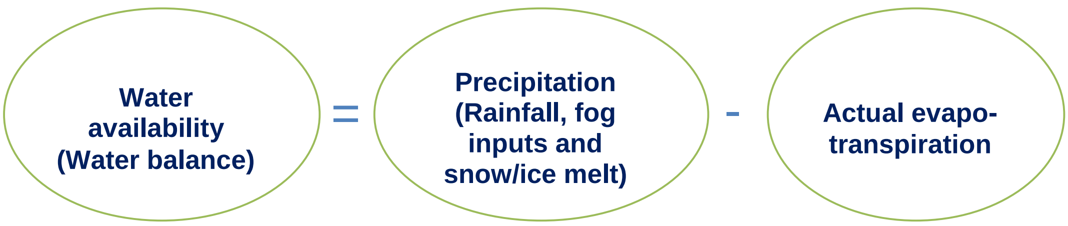


Figure 1-2: An overview of hydrological balance model at the catchment scale

[1] Catchments are also called 'watersheds' or 'river basins', and these terms are used interchangeably throughout the study.

Each variable in fig. 1.2 is measurable, or can be inferred from closing the water balance if the remaining variables are known. Rainfall measurement has a long history of well-developed practices around the world. Fog inputs can be estimated by a recently developed fog interception model (i.e. Fog Interception for the Enhancement of Stream flow in Tropical Areas (FIESTA) model (see, Mulligan and Burke, 2005). There are different measurement practices for evapotranspiration (ET) processes. The ET rates of individual crop varieties can be estimated by using FAO crop ET guidelines (Allen et al., 1998) and for tree crops using the water requirement for trees (Wullschleger et al., 1998). However, challenges remain in terms of quantifying water losses due to ET processes at the catchment scale. Similarly, snow and ice melt is measurable by using a temperature-index based snow model (for example, Hock, 2003 and Yates et al., 2005) and physically based energy budget models (see, Walter et al., 2005).

In a catchment, rainfall and fog inputs are the major sources of water inputs that flow though the landscape in the form of surface runoff and sub-surface storage and flow for aquifers in the downstream areas. Available surface water and soil moisture is first used for the evapotranspiration process from the surface (land and water) and vegetated areas. The ET process is hugely influenced by the different climatic factors such as temperature, cloud frequency and rainfall patterns. After ET, the available water can be used for various hydrological benefits. Thus, local ecosystems directly affect hydrological ESs both through changed quantity and quality attributes of water with direct upstream-downstream linkages. A schematic representation shows the interrelationship between hydrological ESs and terrestrial ecosystems (Fig. 1.3, below).

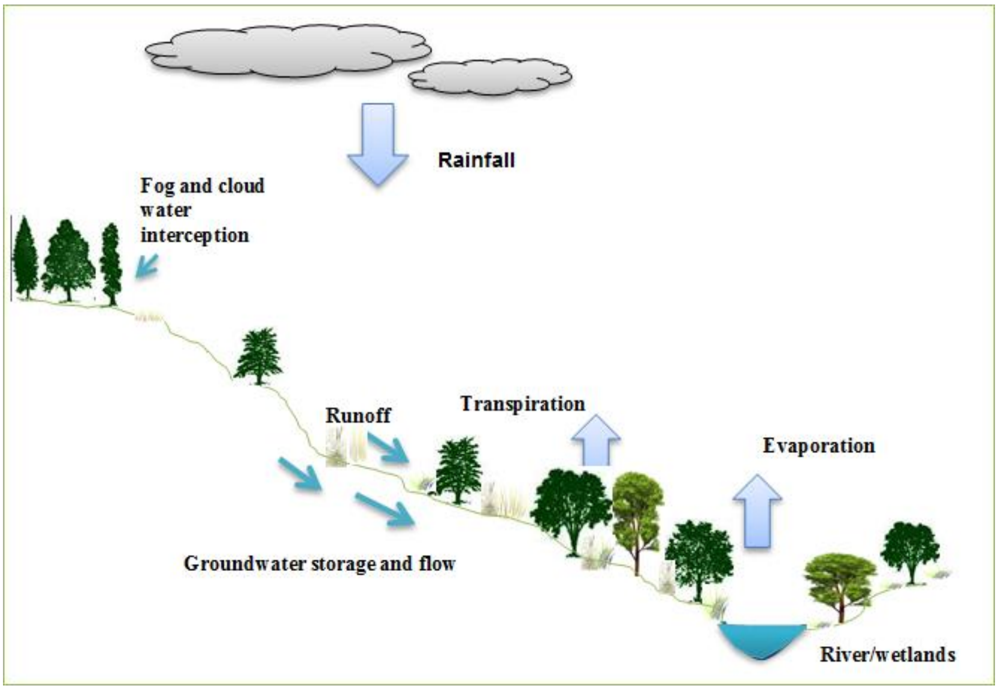


Figure 1-3: A schematic representation of hydrological cycle in a terrestrial ecosystem

Freshwater ESs are being produced during the different stages of hydrological processes. ET related services of crops and vegetation are often neglected due to their virtual presence in the products. Runoff water and groundwater sources are readily available for various provisioning, regulating, supporting and cultural services. Although the local communities are immediate beneficiaries of freshwater services, the actual benefits can be distributed far beyond a basin. The indirect benefits of regulating and supporting services and human appropriation of available freshwater makes it available in a wider "landscape".

Rainfall and other hydrological inputs are transformed into ET services, HEP generation, irrigation, domestic water supply and industrial/commercial benefits. Water diversion through dams and storage channels are being used to produce HEP energy, to irrigated cropland and to supply water to domestic and industrial uses. It is also clear that the water resources use of a catchment is closely linked with demands from inside and outside of the catchment. Once demands are changed, several hydrological services are automatically affected. Discharge to downstream areas is also a major hydrological service to riparian vegetation. The schematic representation of water inputs/outputs and major uses in a human dominated catchments is shown below (Fig. 1.4).

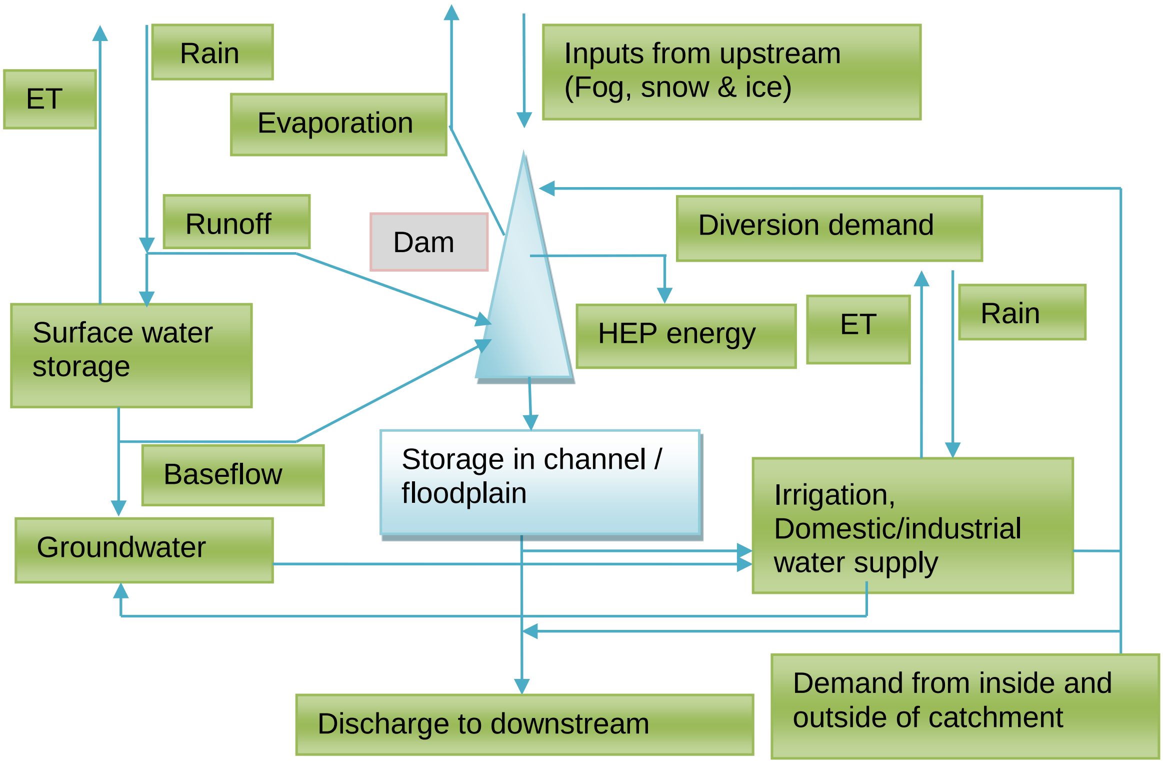


Figure 1-4: A schematic representation of an interrelationship between water input/output and its uses at the catchment scale (adapted from, Kirby et al., 2010)

Water resources coming from watersheds are heavily exploited in the downstream areas which are denser in population and wider in economic activities. Mountains play an important role in the hydrological cycle by storing freshwater in the form of ice and snow and maintaining aquifers and base flow in the downstream areas. Thus, mountains are often called 'water towers' as they provide an important source of freshwater to both upstream and downstream areas. Water services of upstream mountains are hugely significance in arid and semi-arid regions such as the Indian lowlands where vulnerability of seasonal and regional water shortage is very high.

The land use system directly impacts water quantity and quality in a catchment. This affects hydrological ESs to those downstream users and further afield through crop ET services. Upstream farmers are in control of downstream services and that spatial mapping of services provided both in terms of areas and beneficiaries is a useful and important way forward in understanding ESs management in the mountainous regions of the Himalayas.

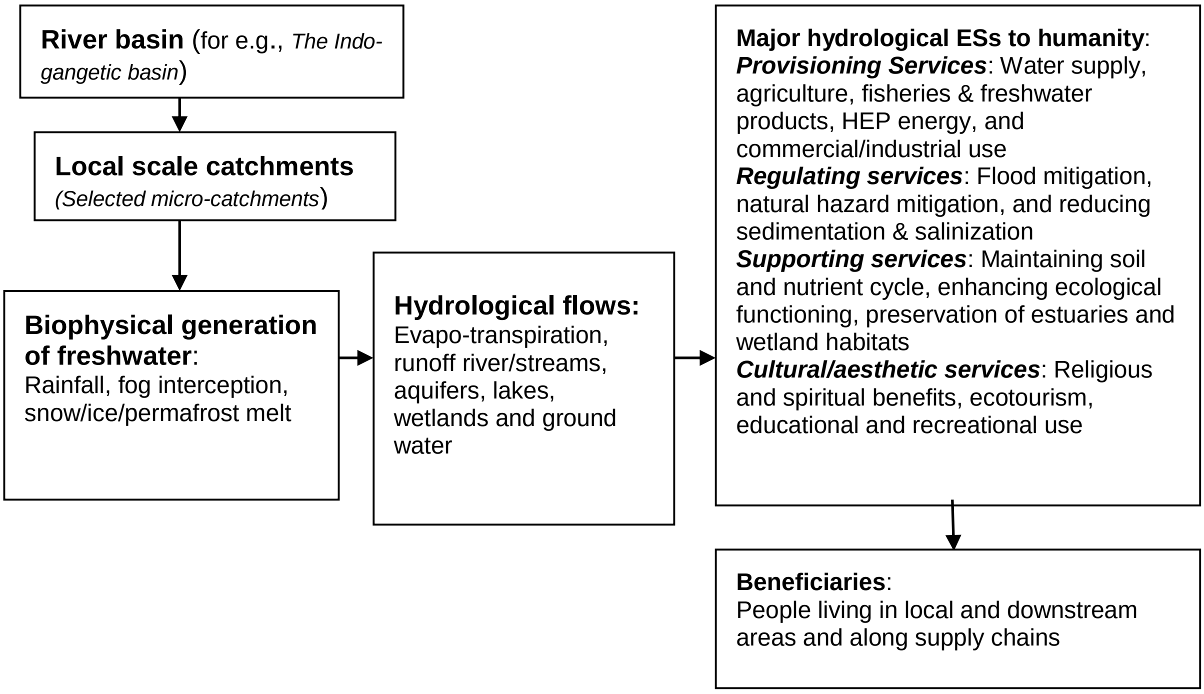


Figure 1-5: A conceptual framework of catchment scale hydrological ESs

Fig.1.5 shows the conceptual framework of the hydrological ESs provided by catchments. At each scale, biophysical generation of freshwater is potentially available in different forms such as rainfall, fog inputs and snow/ice and permafrost melt. The different forms of freshwater are available for human use through the ET sustaining rain-fed crops (green water), runoff, lakes, wetlands and ground water sustaining blue water flows to agriculture, domestic, industry and energy generation. These resources are then converted to hydrological ESs through a range of provisioning, regulating, supporting and cultural/aesthetic services to people living within the catchment and beyond.

1.5.2 Hydrological ESs assessment framework

Although the ESs concept has attracted a huge amount of attention in the science and policy spectrums, there are still many challenges in terms of quantifying these ESs and integrating them into policy agenda. There is a profound gap in the understanding of biophysical characteristics of ecosystems in relation to the services provided which is essential in bridging the science-policy gap (Potschin and Haines-

Young, 2011). Human induced environmental changes have had direct consequences on the functionality of ecosystems and resultant ESs. It is especially challenging for hydrological ESs as land management activities are constantly affecting the amount and quality of water resources. A good understanding of the sensitivity of ecosystem outputs to the different drivers of change in biophysical terms would help to estimate the marginal changes in value between different policy options or management strategies (Potschin and Haines-Young, 2011).

The research has adopted the MA (2005a) definition of hydrological ESs and also recognizes the linkages between eco-hydrological processes and hydrological attributes in order to produce hydrological ESs as illustrated by Brauman et al. (2007). To translate traditional hydrological sciences into an ecosystem services context, it is crucial to understand how a range of eco-hydrological processes may have affected key hydrological ESs attributes. This research also focuses on how plausible future land use changes would affect quantity and certain qualities of water resources. Unlike the definition presented by Boyd and Banzhaf (2007) suggesting that the final products of the ecosystems should be valued, we tend to agree with the more holistic framework for ESs assessment refereed by Fisher et al., (2009). Thus, the research focuses on the quantity and quality related hydrological attributes that underpin many water related ESs.

This research is focused on two major hydrological attributes that have a direct influence on a wide range of hydrological ESs in chosen sites. We estimate the availability of hydrological quantities at local and regional levels and then we also assess the quality attributes (especially sedimentation load and human footprint level) of water resources at local catchments. This leads to policy implications in an effort to maintain or improve hydrological attributes. It may also include PES outlines for mountain catchments where such schemes could support services providers in maintaining hydrological ESs. A conceptual framework for the hydrological ESs assessment is shown in fig 1.6 below.

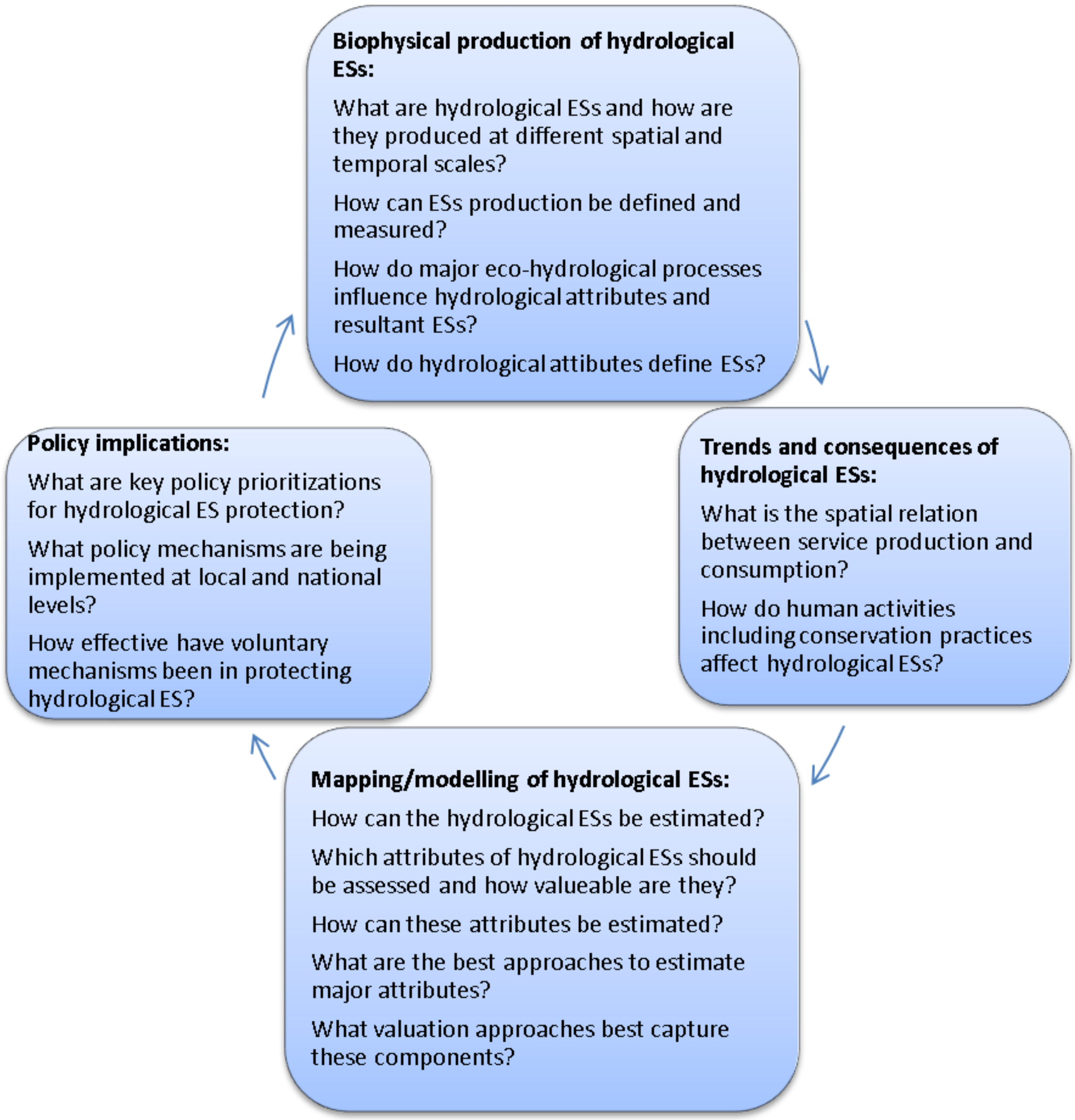


Figure 1-6: A conceptual framework for the hydrological ESs assessment

The conceptual framework adopted for this research represents one means of examining the linkages between hydrological ESs production and land use changes that are both scientifically credible and relevant to the IGB and local sub-catchments in the Himalayas. Quantitative assessment of hydrological attributes would make it easier to evaluate the compatibility of existing water policies established by institutions at different scales.

Ecosystem services are inherently spatial, so mapping/modelling of the services is important for better understanding of linkages between ESs production, delivery and consumption. Without quantitative and spatial analysis across the landscape, ecosystem services tend to be ignored or managed according to simple and potentially inaccurate 'rules of thumb' in policy and decision making processes (Chan et al., 2006 and Crossman et al., 2013). The importance of spatial based mapping/modelling of various ESs has been highlighted in several publications as a promising approach for ESs assessment (e.g., Crossman et al., 2013; Brukhard et al., 2013; Kareiva et al., 2011; Nelson et al., 2009; Tallis and Polasky, 2009; Daily et al., 2009 and Egoh et al., 2008). To deal with the spatial nature of hydrological ESs, we have applied process-based hydrological modelling tools throughout this research.

Policy and decision makers need information about the magnitude of services and their variation in different land management practices (de Groot et al., 2010). It is also important that the hydrological ESs assessments are driven by the needs and constraints of water policy (Brauman et al., 2007). Unlike other ESs such as timber or food services, hydrological ESs are extremely dynamic in nature and can be altered by their interaction with any upstream ecosystem. For that reason, information about the magnitude of ESs production (i.e. the attributes of hydrological ESs) is particularly important. Hydrological ESs can be assessed at different stages of production by measuring generation of ecosystem processes, by quantifying the magnitude of attributes or intermediate services levels, or by assessing the amount of final service benefits. Considering the unique nature of hydrological ESs, this research focuses on the magnitude of two major hydrological attributes quantity and quality (including sedimentation load) of water resources.

1.6 Conclusion

The IGB catchments are some of the most important river basins on earth where water resources are extensively utilized to satisfy a range of human demands such as domestic water supply, crop production, HEP generation and cultural and eco-tourism related ESs. Water resources are mainly available in the form of rainfall/runoff, snow and ice, surface water (such as rivers, lakes and reservoirs), subsurface water flow such as aquifers and groundwater. The regional availability of water resources are hugely variable as the Himalayan foot-hills and the eastern part of the IGB has an abundant water supply compared to its south-western counterparts.

Due to important hydrological ESs based benefits people receive across the basin, their quantitative assessment in plausible land use change scenarios can provide guidance for policy and decision making bodies for better management of both water resources and the sustainable conservation of local catchments. A better understanding of the spatial distribution of hydrological ESs is key to hydrological policies at different geographical scales. Thus, this research is designed to assess the major hydrological ESs provided by the IGB region and the two selected mountain catchments in the middle-mountainous region of the Himalayas.

A theoretical framework has been developed to conduct the hydrological ESs assessment and it is based on regional and local policy needs. Since human interventions, in particular land use change, have had a direct impact on hydrological ESs in the region, a detailed understanding of the magnitude of their impact on quantity and quality related attributes is crucial to water resources based policy and decision making processes. Other key issues such as the geographical distribution of ESs provision, the flow of ESs and the location of beneficiaries are equally important in hydrological ESs assessments. The rationale of the research is also closely related to my own research experience on watershed ESs of the Kulekhani catchment and the need for a spatial based ESs assessment for better policy and decision making processes.

1.7 An outline of the thesis structure

The first chapter introduces the IGB catchments and discusses available water resources in the catchments. The chapter presents the rationale of this research, main aim & objectives, the selection of research sites and a theoretical framework for the research. The chapter explains the rationale of the research in the context of quantitative knowledge of hydrological ESs, geographical distribution of hydrological ESs provisions including their beneficiaries and the policy implications. The importance of selected research sites is also explained as it is crucial for the better understanding of key hydrological ESs at regional and local scales. Then, the chapter presents a clearly articulated research aim, and to achieve it, three key research objectives are developed. It follows with a theoretical framework in which we discuss key concepts around catchment hydrology and hydrological ESs provisions and the adopted hydrological ESs assessment framework for the research.

Chapter Two presents a literature review focusing on the evolution of the ecosystem services concept, an overview of hydrological ESs - particularly concentrating on quantity and quality related hydrological attributes that play a crucial role in hydrological ESs at a catchment scale. Then, it discusses hydrological ESs in the context of terrestrial ecosystems, followed by major factors affecting hydrological ESs such as geographic and hydro-climatic influences, land use and cover change (LUCC) impact and the influence of evapotranspiration processes. After that, it discusses conservation approaches for better hydrological ESs and the evolution of incentive-based ESs policies. The chapter also briefly explains the hydrological ESs based research in the IGB. It includes the importance of water in food and energy security, the use of ESs approach for sustainable development and the potential for a relatively new concept of 'virtual water' in hydrological research and water resources policy for the IGB catchments.

Chapter Three describes the details of data and methodological approaches adopted for this research. Considering the spatial and dynamic nature of hydrological ESs assessments, the research explains why we need a spatially explicit hydrological ESs assessment approach. The chapter describes a selection of appropriate hydrological modelling tools for the selected research sites. Then, it explains the need for scenario modelling using plausible land use change scenarios. Following this, it describes the details of study area delineation and data acquisition and development for the research. After that, the chapter presents methodological approaches used to achieve key research objectives. For the regional scale hydrological modelling, the research has used 1km resolution data and modelling applications whereas 1ha resolution data and model applications are used for the local catchment scale hydrological modelling. In addition, the chapter describes the model specifications of the WaterWorld and Co$ting Nature tools. The chapter also discusses the limitations of data and methods while assessing hydrological ESs of local mountain catchments. Finally, the chapter presents some preliminary modelling results of IGB scale assessment.

In the next three chapters, the research has compiled the major research findings and associated discussions. The research examined hydrological ESs of three different sites which uniquely represented three different types of hydrological ESs. Chapter Four is presenting about the crop ET related hydrological ESs of the IGB catchment. Crop related ESs are an important hydrological ESs to the millions of people within and beyond the basin. The research findings have been published in the Agricultural Water Management Journal (see, Pandeya and Mulligan, 2013). The paper has quantified the water availability at the administrative region scales using a plausible scenario for cropland growth (based on FAO and IWMI projection). Since the water resources are being allocated at state and country levels, the research has calculated the change in water availability at regional administrative scale. Finally, the paper has suggested that if croplands were to increase in the expected way, more efficient use of freshwater would be essential to avoid serious water deficits within the basin.

The chapter follows with local scale hydrological ESs assessment in the middle-mountainous region of the Himalayas. In chapter Five, we assess hydrological ESs assessment of a protected area (PA) catchment. The chapter primarily focuses on domestic water supply to a major urban centre (i.e. Kathmandu). The chapter also discusses the conservation interventions and their impacts on quantity and quality of hydrological ESs. The chapter presents the results of two plausible LUCC scenarios to help understand potential changes in the future. In chapter Six, we assess the hydrological ESs of the Kulekhani catchment – a human dominated area. The chapter also discusses past conservation interventions and their impacts on hydrological ESs. The role of upland communities in watershed conservation is also assessed to understand the contribution played by those communities. The chapter also presents modelling results of an alternative LUCC scenario to assess the change in hydrological ESs. The assessment is primarily focused on change in quantity, water availability and quality (sedimentation load and human footprint level). The chapter examines the relevance between better watershed conservation and self-sustained PES mechanisms for maintaining hydrological ESs in the long-term.

Finally, Chapter Seven restates the aim and objectives of the research, and presents conclusions and major research developments. Then, it discusses major research gaps highlighted in the research and reviews the findings. It follows this by giving key recommendations for the ways forward for the research. In the end, the chapter summarizes the major contributions towards the advancements of scientific knowledge.

Chapter 2 Literature Review

2.1 The evolution of ecosystem services concept

Ecosystem Services (ESs) are the benefits people obtain from ecosystems (Millennium Ecosystem Assessment (MA), 2003). They are the fundamental life support services on earth that provide an array of direct benefits (such as food, fibre, fresh water and shelter), and indirect benefits (such as purification of air and water, climate regulation, pollination, nutrient cycling, pest control and natural hazard regulation) that support and promote the natural resource base (Daily, 1997 and MA, 2005b). Humanity's well-being is directly related to the better functioning of ecosystems and the secured supply of ESs benefits. The MA (2005b) has broadly categorized ESs into four major groups: provisioning services such as food, freshwater and fuelwood; regulating services such as regulation of floods and droughts, water purification, disease regulation and climate regulation; supporting services such as primary production, soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other non-material benefits. However, these services have been seriously affected by human interventions in recent decades and this has resulted in serious consequences for their quality and quantity. The MA has also defined the linkages between ecosystems and human well-being, and clearly stipulated the need for their protection and sustainable use.

The term 'ecosystem services' first emerged in the early 1980s to describe a framework for structuring and synthesizing biophysical understanding of ecosystem processes in terms of human well-being (Mooney and Ehrlich, 1997). Throughout human history, the role of ecosystems in human well-being was clearly reflected by their concerns about the better functioning of surrounding environments and the sufficient supply of ecosystem products (for e.g., see, Feen, 1996 and Redman, 1999). However, the explicit recognition of ESs is a relatively new phenomenon used to describe the biophysical understanding of ecosystems and how they deliver services to human well-being (Mooney and Ehrlich, 1997). Tremendous progress has been made since the MA publication in 2005 in terms of better understanding of ESs both in natural and social sciences as well as in their current and future trends. However, the MA has also highlighted many remaining research needs (Carpenter et al., 2006). Many challenges still remain in the detailed understanding of biophysical production, geographical flow/distribution and the complex relationship between services producers and consumers.

The close dependency of humanity's well-being with various ESs has emphasized the need for a better integration of ES knowledge into decision making processes (Balmford and Bond, 2005 and Daily et al., 2009). The ESs concept has also created an urgent need in deciding how to analyse impacts and trade-offs involved in land cover and land use change, including spatial analysis and dynamic modelling tools (de Groot et al., 2010). Scientific advances around ecosystem service production functions, trade-offs among multiple ecosystem services, and the design of appropriate monitoring programs are increasingly important for the implementation of conservation and development projects that will successfully advance both environmental and social goals (Tallis et al., 2008).The detailed assessment of selected ESs at appropriate spatial and temporal scales may help policy and decision making processes. Moreover, human led environmental change has now become a major driving force in the alteration of natural habitats, ecosystems and resultant ESs (Mooney et al., 2009). It also highlights the need for a detailed mapping of ESs stock, and a flow of services at multiple scales.

The ecosystem benefits people receive are many and varied so their better understanding and integration into policy and decision making process requires systematic categorization and an appropriate assessment framework. The MA (2005b) has categorized all ESs benefits into four major groups of provisioning, regulating, supporting and cultural/aesthetic benefits. Alternative classification systems also exist based on various priorities such as environmental accounting, intermediary services, interest of ESs and a decision context (see, Boyd and Banzhaf, 2007; Wallace, 2007 and Fisher et al., 2009). Using an appropriate classification system would be crucial for valuing ESs benefits and comparing them with alternative management practices/scenarios.

The ecosystem services framework is a major approach in improving the understanding of the complex relationship of ESs production, delivery and consumption. Different approaches have been developed; some argued that the ESs framework should include only the final products of ecosystem processes (Boyd and Banzhaf, 2007) and others argued that not only the final products, but also the intermediary products such as regulatory services should be considered as ESs (Fisher et al., 2009). Recognizing supporting services is essential in managing and maintaining the delivery of ecosystem 'end products'. Beyond the biophysical nature of ESs production, the impacts and trade-offs with human use are fraught with human interventions and various practical and ethical considerations. Different valuation and scenario analysis methods have been developed to inform decision making in an effort to maintain and improve the ESs.

2.2 An overview of hydrological ecosystem services

Hydrological ecosystem services are the types of ecosystem services (ESs) enabled by a variety of surface freshwater resources as well as underground water reserves (Postel and Carpenter, 1997; Millennium Ecosystem Assessment (MA), 2005a and Brauman et al., 2007). Water resources, including wetland areas, deliver a range of ecosystem services that contribute to human well-being, such as fish and fibre, water supply, water purification, climate regulation, flood regulation, erosion control, recreational opportunities and tourism (MA, 2005a). The MA has categorized these services into four major groups such as provisioning, regulating, cultural and supporting services (table 2.1, below).

Table 2-1: Major hydrological ESs provided by or derived from water and wetlands (Source; MA, 2005a)

Services	Comments and Examples
Provisioning	
Food	Production of fish, wild game, fruits and grains
Freshwater	Storage of retention of water for domestic, industrial and agricultural use
Fibre and fuel	Production of logs, fuelwood, peat, fodder
Biochemical	Extraction of medicines and other materials from biota
Genetic materials	Genes for resistance to plant pathogens, ornamental species
Regulating	
Climate regulation	Source of and sink for greenhouse gases; influence local and regional temperature, precipitation and other climatic processes
Water regulation (hydrological flows)	Groundwater recharge/discharge
Water purification and waste treatment	Retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	Retention of soils and sediments
Natural hazard regulation	Food control, storm protection
Pollination	Habitat for pollinators
Cultural	
Spiritual and inspiration	Source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	Opportunities for recreational activities
Aesthetic	Many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	Opportunities for formal and informal education and training

Supporting	
Soil formation	Sediment retention and accumulation of organic matter
Nutrient cycling	Storage, recycling, processing, and acquisition of nutrients

A secured and good quality water supply provides a range of essential ESs to humanity. Provisioning services are the direct benefits people receive from different uses such as domestic, crop production, livestock raising, fisheries production, hydro-power generation and industrial. Regulating services mainly include water purification, maintaining surface and groundwater flow and the control of water borne hazards. Similarly, freshwater provides cultural and amenity services that include spiritual value, recreational benefits, cultural heritage and educational inspiration. Finally, freshwater resources also provide supporting services by maintaining ecological functioning and habitat protection.

Although the MA (2005a) broadly defines hydrological ESs, it lacks the proper discussion of how a range of eco-hydrological processes affect key hydrological attributes such as quantity, quality, geographical distribution (location) and the timing of hydrological resources which together underpin hydrological ESs. Brauman et al., (2007) have illustrated the linkages between eco-hydrological processes and key hydrological attributes and they have also categorized hydrological ESs into diverted water supply, in-stream water supply, water damage mitigation, spiritual and aesthetic services and supporting services (table 2.2, below).

Table 2-2: The relationship between major hydrological/ecological processes, hydrological attributes and hydrological ES benefits (Source; Brauman et al., 2007)

<table>
<tr><th>Eco-hydrological processes →</th><th>Hydrological attributes →</th><th>Hydrological ES benefits</th></tr>
<tr><td>Local climatic interactions
Water use by crops/plants</td><td>Quantity (rainfall, fog, snow/ice, evapo-transpiration, surface and ground water storage, drainage system)</td><td rowspan="3">Diverted water supply: Water for municipality, agriculture, commercial, industrial, HEP power generation

In-situ water supply: Water for hydropower, recreation, transportation, supply of fish and other freshwater products

Water damage mitigation: Reduction of flood damage, dry land salinization, saltwater intrusion, sedimentation

Spiritual and aesthetic: Provision of religious, education</td></tr>
<tr><td>Environmental filtration
Soil Stabilization
Chemical and biological additions/subtractions</td><td>Quality (pathogens, nutrients, salinity, sediment)</td></tr>
<tr><td>Soil development
Ground surface modification
Surface flow path alteration
River bank development</td><td>Location (ground/surface, up/downstream, in/out of channel)</td></tr>
</table>

Control of flow speed Short- and long-term water storage Seasonality of water use	**Timing** (peak flows, base flows, velocity)	and tourism values **Supporting**: Water and nutrients to support vital estuaries and other habitats, preservation of options

Eco-hydrological processes are the phenomenon of ecological and hydro-climatic interactions with terrestrial ecosystems and thus ensuring quantity, quality, location and timing of hydrological services (Brauman et al., 2007). On the one hand, local climatic interactions and evapotranspiration processes directly alter the water availability in the catchment as well as in the downstream area; on the other hand, environmental filtration, soil stabilization and various pollutants (both chemical and biological) directly affect water quality. Similarly, a range of catchment modification activities such as land management practices, surface flow path alteration and river embankments may alter the location of water availability. Finally, the seasonality of hydrological inputs, storage systems and various control measures affect the timing of water availability. Each hydrological ES is directly or indirectly related to the quantity, quality, location and timing of water flow. A better understanding of hydrological attributes in the context of human intervention is therefore crucial for better policy and decision making processes.

2.2.1 Water quantity

The amount of water available for various provisioning services such as water supply for domestic consumption or crop cultivation is a key hydrological attribute. In a terrestrial environment, the quantity of water is directly affected by various eco-hydrological processes. Human appropriation of surface and groundwater resources through extensive use, reuse and diversion also immensely changes the amount of water availability within and beyond river basins. The amount of water can be hugely altered in human dominated catchments where human appropriation plays a central role. Some freshwater ESs are largely defined on the basis of quantity, for example, increased freshwater volume is good for water supply systems in water deficient areas but less water is good for flood mitigation in flood prone regions. The quantity is critically important for arid and semiarid regions where naturally available water is very low to satisfy both natural and human needs.

Hydro-climatic interactions directly affect the amount of water available at the catchment scale. Fog water input and snow & ice melt increase the amount of water available in the basin. Fog water input is a process of fog deposition and/or interception while passing through cloud affected forests in a suitable climatic condition. It contributes a small addition (<5%) in some central American regions (Mulligan and Burke, 2005) but the contribution can be up to 34% (with trees) and 17% (without trees) in the coastal redwood forest areas of California (Dawson, 1998). Hydrological inputs of cloud forests are of minor importance to catchments where the upstream areas receive high rainfall but it can be significant (especially seasonally) to the catchments where these areas are dry (Mulligan and Burke, 2005). Snow and ice melt are also important means of water input at the basin scale. They provide inter and intra-annual water supply which is crucial to the semi-arid and arid downstream areas where very little or no rainfall occurs throughout the year.

Annual water balance is the amount of water (after ET processes) that can be available for various uses. Both natural and human dominated ecosystems have a significant impact on water quantity but at different levels (Allan, 2004). Spatially, all ecosystems have higher impacts at local scales but a low to negligible impact at regional scales where climate and terrain dominate (Brauman et al., 2007). While higher vegetation coverage (e.g. forested areas) consume a huge amount of available freshwater in the ET process, low vegetation coverage such as grassland needs comparatively less water (Calder, 2002 and Costa et al., 2003). Such hydrological impacts ultimately change the annual total water balance. Thus, human dominated landscapes (primarily cropland) may have major impacts on water quantity. Water use in the cropland ET process is moderate to high (depending on the types of crops and the level of irrigation) and thus cropland can lead to less water available in downstream areas.

Land use change is a major factor that can alter actual evapotranspiration (AET) rates. Higher vegetation coverage consumes more water and results in lower water balance. Afforestation and deforestation processes are drivers of change in water availability at local and catchment scales. The greatest stream water yield or ground-water table changes occur immediately after forest land disturbances but changes are less while applying silvicultural operations on wetlands (Sun et al., 2004). The interrelationship between forests and water balance has been long debated - forested landscapes produce less water compared to grass or shrub lands (Calder, 1999; Calder, 2002 and Andréassian 2004) because of higher ET. In conclusion, freshwater quantity services are highly affected by land cover.

2.2.2 Water quality

The quality of freshwater is also an important attribute that directly relates to human health and well-being. It includes various components such as the level of chemicals, nutrients, microbial presence and sedimentation processes. Although the good quality water is desirable for many hydrological ESs provisions, it is essential for direct uses such as drinking water and sanitation purposes. The quality of surface and groundwater resources are directly or indirectly affected by terrestrial ecosystems. A large scale change in land management can have a greater impact on freshwater quality. Human dominated ecosystems such as cropland and urban areas have detrimental impacts on freshwater quality compared to forested catchments (Sliva and Dudley Williams, 2001). But, the implementation of conservation area programmes could generate some positive impact on freshwater quality where protection reduces the potential impacts coming from human settlement and agricultural lands. Intact vegetation coverage may also produce good quality water by filtering sediments and reducing inputs from agriculture.

Human interventions in watershed areas can add or remove a variety of contaminants on surface and groundwater sources. Watershed conservation activities play an important role in hydrological ESs by either improving water quality through filtration or maintaining them through a limited addition of contaminants to the stream. Forest cover in upland areas generally improve slope stability by reducing the intensity of rainfall (Keim and Skaugset, 2003). When forest cover is reduced, soil erosion will increase. Changes in the annual sedimentation ratio is an indicator of how water provisioning services are benefited in the downstream areas. However, the effect of ecosystems on water quality is a continuous process and measuring such effects would require a long-term data collection and analysis framework. Where such measurements are not possible, modelling techniques can be applied to estimate erosion and sedimentation level in available water resources.

2.3 Hydrological services in terrestrial environments

Freshwaters represent about 7% of the earth’s surface area which include surface water (such as rivers, lakes and reservoirs) and groundwater reserves (Carpenter and Biggs, 2009). Terrestrial ecosystems directly or indirectly contribute to hydrological inputs and outputs. Freshwater is a renewable resource but is in limited supply at any one time and has a close relationship with people and environment

(Oki and Kanae, 2006). People now use about 50% of the earth's available renewable freshwater, but this proportion exceeds 100% in some arid regions (Oki and Kanae, 2006 and Carpenter and Biggs, 2009). Since the demand for water is continuing to grow, there will be more pressure on available water resources.

Globally, only 2.5% of the earth's water resources are fresh, and of that, 68.7% is locked up in the form of ice and permanent snow cover in the Antarctic, Arctic and mountainous regions, about 29.9% is groundwater, and only 0.26% of freshwater is easily accessible for human use (Shiklomanov, 2000). Accessible freshwater resources are confined to lakes, reservoirs and river systems. In recent decades, constructed reservoirs and temporary storage facilities have also become key sources of freshwater especially in arid and semi-arid regions. Precipitation is the only source of all freshwater (except for some groundwater such as deep underground or fossil water) that renews the freshwater resources seasonally. Whilst there is a huge presence of freshwater in river basins, in reality, humanity can exploit only a limited fraction of water because of geographical and temporal constraints or the lack of storage facilities (Alcamo et al., 2005).

Mountains are commonly regarded as the prime source of freshwater resources. About 80% of freshwater for human use comes from mountain catchments (Postel and Thompson, 2005), and as water flows to downstream areas, which are more densely populated and wider in economic activities, water resources are heavily exploited to fulfil humanity's demands. On the one hand, higher slope gradients and steep valleys in the upland areas are favourable for the development of HEP facilities. On the other hand, water resources are extensively diverted for domestic water supply, irrigation and economic activities in the downstream areas. However, the benefits are highly contextual and depend on various factors such as location and suitability of water based infrastructural development.

Generally, the hydrological ESs of a landscape can be divided into two major categories; blue water services from runoff water and green water services (supporting crop production) through the ET processes of vegetation, land surface and water bodies (Falkenmark, 2000). The 'blue water' services are easily recognized by contemporary market mechanisms for their various provisioning services (irrigation, HEP, domestic supply). However, 'green water', which plays a key role in water balance, is long neglected in water resources policy. Some research has estimated that terrestrial ET required for the crop production process consumes a majority (up to

60%) of rain water (Brutsaert, 1986 and Rockström et al., 1999). It is highly variable depending on vegetation structures, crop varieties, biophysical and hydro-climatic variation.

The current state and future prospect of hydrological dynamics in relation to human induced impacts and key hydrological ESs have been widely illustrated in various studies (See, Postel and Carpenter, 1997; MA, 2005 a & b; Aylward et al., 2005; WWAP, 2006 & 2009 and FAO, 2011 & 2012). Many ecosystems including cropland, forest and pasture are heavily dependent on sufficient levels of freshwater supply. In terms of human use of freshwater resources, agriculture is the single most dominant use sector consuming more than 70% of total freshwater consumption worldwide (WWAP, 2009). Other key areas of freshwater uses include domestic water supply, HEP generation and industrial usage. Agricultural water use is consumptive and the evapo-transpired water is no longer available for reuse in downstream, whereas industrial and domestic use is returned to the system and can thus be used multiple times from source to mouth of a river basin.

Climate change is a major affecting factor that has a high degree of potential impact on freshwater and other ecosystems (Kundzewicz et al., 2008). Semi-arid and arid areas will experience more vulnerability where a small change in the hydrological cycle may create significant problems associated with the freshwater resources and ecosystems. Climate-driven hydrological changes will also combine with other pressures such as population growth, land-use change and life style improvement which ultimately puts more pressure on allocation of available freshwater resources (Kundzewicz et al., 2008). Such climatic impacts would have severe consequences on hydrological ESs, especially in the water deficient areas of the Indus basin.

There is a growing concern of secured water supply in human dominated catchments due to an extensive scale of catchment modification and river diversion schemes (Goudie, 2013). Unsustainable activities may have resulted in depletion and pollution of water resources along the river channel. Some eco-hydrological features also have a direct role on water production, for example, the conservation of cloud affected forests have a positive impact on hydrological services for downstream dams (Saenz and Mulligan, 2013). Water supply in well-managed cloud affected forests is better regulated, and has direct benefits to downstream beneficiaries. Understanding of such hydrological processes can improve the current knowledge about water resources production in human dominated mountainous regions of the Himalayas.

2.4 Major factors affecting hydrological ESs at catchment scale

2.4.1 Geographic and hydro-climatic variability

Geographical and hydro-climatic variability always plays an important role in hydrological ESs. Stream flow distribution spatially and seasonally of a basin experiencing only rainfall is different from a basin having contributions from rainfall, snowfall and glacier inputs. In the same way, the catchments where temperature and precipitation characteristics are such that snow accumulation in the preceding winter is completely melted away, in addition to the next spring and summer months having different stream flow pattern to those catchments where all the accumulated snow and ice has not melted away in the following year (Singh and Kumar, 1997).

Hydrological services generated by mountain catchments are affected by an extraordinary heterogeneity of topography, seasonal and annual climatic variability, vegetation and soil types, and spatially and temporally differentiated snow-cover (Gurtz et al., 2003 and Messerli et al., 2004). Similarly, mountains have a direct influence on hydrological systems of a much larger surrounding area by acting as a physical barrier to atmospheric flow, thus higher catchments receive large amounts of water (Viviroli et al., 2007). In addition, the availability of large volumes of snowmelt has given a perennial character to the rivers. Mountains have disproportionately large discharge, typically about twice the amount that could be expected from the areal proportion of the mountain section in most catchments (Messerli et al., 2004). Mountains account for 20-50% of total discharge in humid areas, while in semi-arid and arid areas, the contribution of mountains to total discharge are 50-90% with extremes of over 90% in some river basins (Viviroli et al., 2003). The Indus basin is one such where upper catchments (i.e. the Himalayas) contribute most of the river flow during the dry season of the year. The available river water is being extensively diverted for irrigation and other uses in the densely populated lowland areas. As the demand of water is growing across the basin, there would be a direct consequence on water availability in the downstream areas of the basin.

Regional climatic variability is also a key factor in determining the fluctuation in water balance throughout the year. For example, in tropical regions, fog or rain that is intercepted by cloud forest canopy, and can drip to the ground or evaporate directly from the leaf surface, is vital to the total amount of water available in uplands as well as downstream areas (Roberts et al., 2004). Tropical montane cloud forests are also characterised by low evapotranspiration rates, and are located in high precipitation areas, thus producing high volumes of water in the headwater areas (Mulligan and Burke, 2005). It has been suggested that the collection of fog water input can help communities in the water deficient remote mountainous region of Nepal (see Apigian, 2005). However, there is a lack of detailed study about the level of fog water contributions in annual water balance in the region.

Moreover, the AET of most arid and semi-arid lands is greater than the average precipitation received, and that phenomenon affects water balance negatively. Water deficiency is frequent in such areas. AET is dependent on available energy in the form of solar radiation (based on latitude, elevation, topography and cloud frequency), vegetation coverage and water availability. In the lower Indus basin where annual precipitation is extremely low (below 100 mm/yr) water scarcity is very high. In such a hydro-climatic environment, human appropriation of water resources through river diversion and the extraction of deep groundwater sources can maintain many freshwater ESs.

2.4.2 Land use and cover change

Land use and cover change (LUCC) has a considerable impact on water quantity (the lower the vegetation cover – the lower the ET in general) and quality (croplands and pastures often have a negative impact) (Foley et al., 2005). Hydrological regimes can be altered due to vegetation changes such as afforestation, deforestation, re-growth and whole forest conversions which can have a crucial impact on annual water yield (Brown et al., 2005). Several previous studies on surface water flow in paired catchments have shown that there is a significant loss of stream discharge (up to 45%) when grassland is converted into forestland (Bosch and Hewlett, 1982 and Costa et al., 2003 and Farley et al. 2005). The loss of water yield is much higher in low flow areas of semi-arid catchments (Brown et al., 2005). Similarly, young and invasive plants also have larger impacts on water quantity, by more rapidly transpiring water, compared with mature vegetation coverage (Vertessy et al., 2001 and Calder and Dye, 2001). As a result, the water availability within the catchment and in the downstream areas is altered, which in turn has a direct impact on hydrological ESs. Understanding such impacts at the appropriate catchment scale would support decision makers to better integrate science into the land management policy arena.

Land use change - and particularly vegetation cover change - is one of the major factors that also affects runoff flow and groundwater storage (Dunn and Mackay, 1995 and DeFries and Eshleman, 2004). Catchment scale experiments from around the world have also proven the direct relationship between vegetation cover, long-term average evapotranspiration and water balance at the basin scale (Zhang et al., 2001). Dense forests (except cloud forests) with large trees use more water than lower statured vegetation (Calder, 2002 and Calder, 1999), thus in a water-scarce catchment, vegetation may reduce water availability in the downstream areas. As a result, the surface and groundwater availability from a forested catchment is often lower than that from grass and shrub-dominated catchments (Andréassian, 2004), at least as an annual average. The higher the vegetation coverage the greater the evapotranspiration rate; so less water is available for other water uses in lowland areas.

The crops and natural vegetation consume a huge amount of freshwater through transpiration (trading water for biomass), thereby producing valuable services to people (Falkenmark, 2000 and Falkenmark and Rockstrom, 2006). In the IGB, crop production has a significant influence on water balance. Due to intensive crop cultivation practices, less water is available for a wide range of water-based activities in the downstream areas. A huge amount of freshwater consumption in the ET process is transformed into virtual water services of the resulting crop products which benefit people across the geographical regions. This research is trying to estimate the level of water consumption in cropland at the regional administrative scale.

Biophysical characteristics of a catchment also have a direct impact on hydrological properties. Despite the fact that there is a direct hydrological response if large-scale vegetation cover change takes place, a key control on water volume remains as topography, soil and geology (Bruijnzeel, 2004). The value of forest conservation in upland areas also needs to be expressed in terms of their benefits for better water quality and various regulatory and supporting services rather than the change in water quantity services alone (Bruijnzeel et al., 2006 and Bruijnzeel et al., 2011). To understand such services, there is a need for a detailed study on how watershed conservation activities have affected erosion and sedimentation processes. Similarly, analysing the human footprint (i.e. various human interventions in the catchment) is also helpful in investigating the impact of human activities on water resources.

Traditionally, there is a public misperception regarding the role of forested catchments on water services in that the forest protection increases the water flow (Calder, 2002). An increased ET rate in upland areas may diminish the level of water availability within and in the downstream of the catchment. However, the impact of forest on water services depends on hydro-climatic characteristics. Recent studies have recognized the hydro-climatic processes of montane cloud-affected forests (*sensu,* Mulligan and Burke, 2005 and Bruijnzeel et al., 2011). This means that evapotranspiration is slightly increased by forest cover (because of low solar radiation) but additional cloud water inputs by fog water interception/impaction can tip the balance and enhances catchment runoff (see, Bruijnzeel, 1990; Bruijnzeel and Proctor, 1995; Bruijnzeel et al., 2006; Bruijnzeel et al., 2011 and Sáenz and Mulligan 2013).

Fog water input (Cloud Water Interception – CWI effect) is a key hydrological process which may have a substantial effect on the hydrological cycle in suitable hydro-climatic and biophysical environments (Bruijnzeel et al., 2011). There are a considerable amount of detailed studies done about the impact of tropical montane forests on fog water inputs (see, Bruijnzeel, 2004; Mulligan and Burke, 2005 and Bruijnzeel et al., 2011).The CWI effect of mountain forests is largely ignored in hydrological science but makes an important distinction between the hydrological behaviour of lowland and mountain forests. In the middle-mountainous region of the Himalayas, such cloud water interception effects may have a significant role in the annual water balance. It is therefore important to explore the level of its contribution in regards to hydrological ESs. It is possible to understand the contribution of fog water inputs using hydrological modelling tools with required datasets. This research is trying to fulfill the research gap through estimating fog water input of selected mountainous catchments in the Himalayas.

2.5 Watershed conservation for hydrological ESs

Conservation approaches are well recognized all over the world for their key role in protecting and delivering a range of ecosystem services including safeguarding freshwater resources (De Groot et al., 2002; MA, 2005a and MA 2005b). Different conservation approaches including nature reserves, parks, preserves, and refuges exist depending on their key functions (Phillips, 2004). In many cases, the designation of watersheds for conservation areas are also closely related to the improvement of freshwater ecosystem services (Dudley and Stolton, 2003). The importance of forest protected areas for good quality water supply has been well documented in various studies (for e.g., Dudley and Stolton, 2003; Postel and Thompson, 2005 and Muñoz-Piña et al. 2008). In an increasingly anthropocentric world where the human population is ever growing, life style is rapidly changing and economic activities are expanding, maintaining a good quality water supply is more important for current and future generations. In such a scenario, it is crucially important to understand the role of conservation activities on hydrological ESs.

Although the designation of protected areas are largely based on the conservation of rare and endangered biological diversities, the positive impact of forests and other vegetation cover on good quality water supplies have further strengthened the arguments for the conservation of watershed areas (Pagiola, 2008). In those PAs, where human settlements exist within the park boundary, conservation practice requires a delicate balance between maintaining conservation status and improving local livelihoods. The supply of improved ecosystem services requires a balance between conservation activities and sustainable livelihoods in and around the park (Dudley and Stolton, 2003). In such a scenario, an effective ecosystem services based approach supported by major stakeholders (i.e. upland communities and downstream beneficiaries) could make conservation activities more sustainable. At the same time, the conditions of various ecosystem services including freshwater ESs would be better maintained for their users.

Watershed protection activities are credited with the regulation of the hydrological cycle, water quality maintaining, habitat protection, and soil erosion control (Pagiola *et al.*, 2002 and Postel and Thompson, 2005). To capture various watershed level services, markets have been evolved in various forms. Watershed protection services are distributed mostly at the local, regional and river basin levels. Among many watershed benefits, a good forest helps to slow the surface runoff; reduce soil erosion and sedimentation; increase water infiltration and influence water chemistry; and increase groundwater recharge (Scherr et al., 2004 and Postel and Thompson, 2005). Despite the regulatory function, forests may reduce the total stream flow, especially because of the excessive transpiration effect (Calder, 2002). Watershed services have also played a key role in reducing vulnerability, flooding and soil degradation.

The market potential of watershed protection services has been increased throughout the world. Since there is a huge demand for clean drinking water in IGB countries, the potential market of watershed services will continue to grow in the near future. Moreover, hydropower projects, irrigation facilities and other water resources related infrastructures are dependent on good watershed services.

2.6 The evolution of incentive-based conservation approaches

Conventional environmental management practices and even Integrated Conservation and Development Programmes (ICDPs) have failed to reward ESs providers appropriately (Landell-Mills and Porras, 2002). Community-based conservation approaches are also not effective because of their financial problems in sustaining conservation activities (Ferraro and Simpson, 2002). As a result, new means of market concepts have emerged to provide direct incentives to service providers for their commitment in the continuing delivery of environmental services (Wunder, 2005; Swallow *et al.*, 2007 and Jack et al., 2008). The strong and growing interest in developing these markets is driven by frustrations with traditional regulatory approaches, a growing recognition of the limits of protected area approaches to conservation, societal demands for ecologically sound products, and the forest-based industry's need to find additional revenue sources to remain competitive (Scherr *et al*., 2004).

Direct approaches to conservation are not just based on the cost of ecosystem management but they also aim to offset the opportunity costs that conservation incurs at the local level (Wunder, 2005 and Engel et al., 2008). A large amount of literature has expressed the market potential of incentive-based conservation schemes over traditional conservation approaches (see, Ferraro, 2001; Ferraro and Kiss, 2002 and 2003; Ferraro and Simpson, 2002; Scherr et al., 2004; Niesten and Rice, 2004 and Spiteri and Nepal, 2006). Ferraro and Simpson (2002) argue that conventional conservation subsidies are becoming less reliable, while incentive-based conservation approaches are far more cost-effective. However, such incentive-based programmes have been implemented with little consideration for their ability to fulfil promises of conservation, equitable benefit sharing issues and long-term sustainability of programmes (Spiteri and Nepal, 2006).

As wilderness and natural habitats have declined, many positive externalities previously provided freely by nature are becoming increasingly threatened (Wunder, 2005). The emerging scarcity of environmental externalities makes it important to secure them from further deterioration. Another aspect of market development is that the people adjacent to those services have invested their efforts in conserving them, but without any reward (Landell-Mills and Porras, 2002 and Turpie et al., 2008). The benefits derived from these services are enjoyed at various geographical scales. The resource managers, on the other hand, are relatively poor and lack any voice at the policy-making level.

In such a newly emerging scenario, incentive-based conservation concepts have been evolving with the principal aim of compensating the conservation efforts of local people. As most ecosystem services are difficult to measure in contemporary market regulations, the payments are mostly on a voluntary basis (Wunder, 2005). Payment for environmental services (PES) is defined as:

> '…*a voluntary transaction in which a well-defined environmental service (ESs), or a form of land use to secure that service is bought by at least one ESs buyer from a minimum of one ESs provider, if and only if the provider continues to supply that service*' (Wunder, 2005, p. 3).

The PES approach has attracted increasing interest as a mechanism to translate external, non-market values of the environment into real financial incentives for local actors to provide ESs (Engel et al., 2008). An incentive-based conservation approach in which a HEP producer pays upstream communities to conserve the watershed above its plant would be an example of a good PES programme. Thus, a PES attempts to internalize what would otherwise be an externality (Pagiola and Paltais, 2007). It offers local communities a direct and more equitable approach for achieving environmental outcomes in comparison to other traditional approaches (Jack et al., 2008).

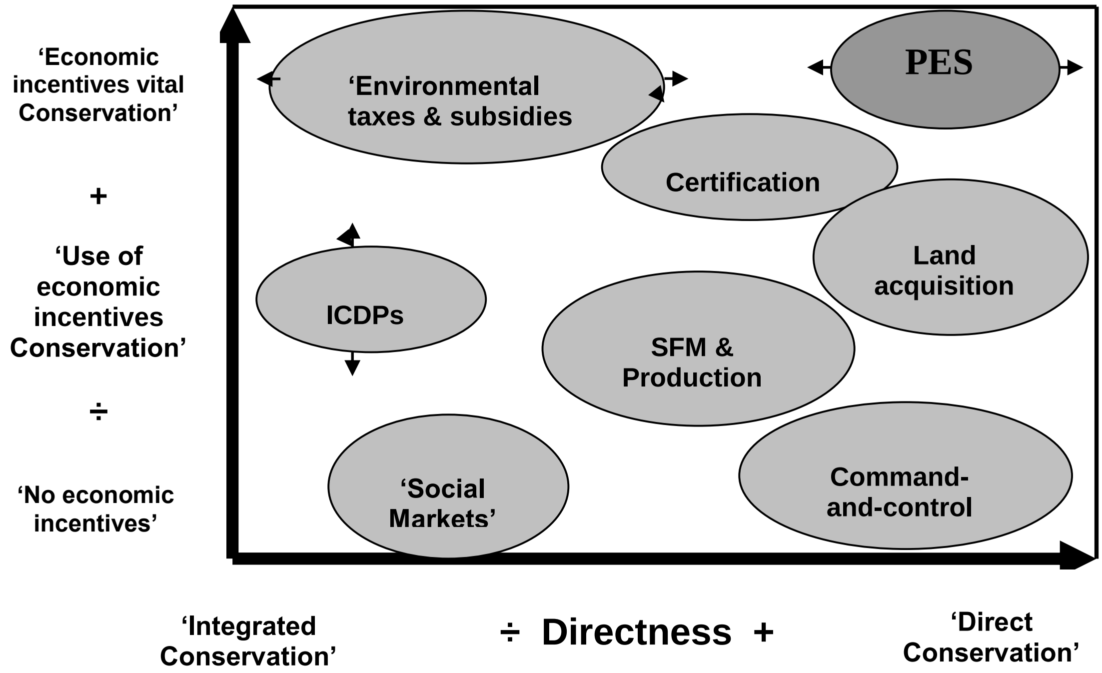


Figure 2-1: Comparing PES approach to other conservation approaches (Source: Wunder, 2005)

The comparative position of the PES vis-à-vis other conservation approaches have been presented in fig. 2.1. The position of various conservation instruments is defined based on their dependency on economic incentives and the extent to which conservation has been directly targeted rather than being integrated into other developmental approaches. The command-and-control regulations (including strictly protected areas) are a rather direct approach but without using economic incentives (Wunder, 2005). On the other hand, ICDPs are a less direct approach with holistic efforts and explicit integration of conservation and development activities. These approaches are also focused on building a local institutional capacity, generating local goodwill towards conservation and influencing government policies. Fewer economic incentives are used in ICDP approaches to generate conservation and development goals. By contrast, 'Social Markets' are less economic and often characterized as traditional systems evolved from indigenous practices over time (Heyman and Ariely, 2004). Several other approaches such as sustainable forest management (SFM), land acquisition for conservation, certification and various environmental taxes and subsides are placed in between, and are moderate in economic incentive use and directness. On the other hand, the PES schemes are regarded as a highly promising and direct conservational approach and vital to economic incentives (Wunder, 2005).

The PES scheme has contributed in attracting political support for conservation, but also to monetize a growing number of ESs and to reproduce a new economic paradigm to tackle environmental issues (Gomez-Gaggethun et al., 2010). Despite the rapid growth of PES approaches around the world, the success of the programmes are rather contextual in terms of achieving successes in conservation activities, sustainable development and poverty alleviation goals (Landell-Mills and Porras, 2002 and Bulte et al., 2008). Thus, the PES scheme should have clear and achievable goals for maintaining/improving ESs provisions and to achieve associated goals. Since the main aim of the research is about the linkages between watershed conservation and their impacts on hydrological ESs, any interpretation of the prospect of PES is directly related to a better delivery of hydrological ESs at the catchment scale.

2.7 Hydrological ESs of the IGB

2.7.1 Food, water and energy security

The IGB catchments have been characterised as one of the world's poorest regions. The region also hosts the majority of underprivileged people from South Asia (which has more than 40% of world's poorest) who are largely dependent on subsistence farming and indigenous based land-water management practices for their livelihood (Rasul, 2012). While the region has been experiencing higher population growth and increased pressure on land and water resources, other equally important and more disturbing trends are prevalent with respect to socio-economic and human development indices (UNDP, 2011). The demand for freshwater related services in the region is rapidly increasing primarily due to unprecedented population growth, changing diets and lifestyles and economic expansion. The challenge is how to minimize trade-offs and maximize synergies between demand and consumption of freshwater resources and sustainable development. For that, it is necessary to understand how food, water and energy are related within the basin.

The IGB region faces difficult challenges to meet a growing demand for food, water and energy in the face of growing population pressure, socio-economic changes and also progressive climate change (Rasul, 2012). About 51% of IGB population is still in a food-energy deficient situation (Ahmed et al., 2007) and 20% lacks access to safe drinking water (Babel and Wahid, 2008). Thus, any large scale disturbance in the water, food and energy nexus may create regional and global consequences of food supply and health related problems. The region will have to produce more foods with the same (or less) land and water resources in coming decades. Such pressure will create crop intensification and increased groundwater extraction to an unprecedented level.

In the IGB plains, water use is dominated by agriculture (estimated at 91%), followed by domestic uses (estimated at 7.8%) (Eastham et al., 2010 a & b). The IGB has the largest irrigated agricultural systems on earth which primarily depend on monsoon rainfall and water coming from the uplands (i.e. the Himalayas). A large part of the IGB croplands is comprised of intensive rice and wheat cultivation which requires a huge amount of water supply. In the middle-hills region, the major farming systems are rain-fed and irrigated cropland (mixed with rice and wheat). The demand for freshwater in the agricultural sector is expected to increase by 50% in next few decades to satisfy the additional food demand from population increases (Nellemann and Kaltenborn, 2009). This shows the important role played by freshwater resources in the food security of the region. However, there is a substantial research gap on how much water is being used in the crop ET process - a major source of agricultural water consumption at the basin scale.

HEP supply is a major source of clean energy and currently it provides around 20% of the global energy supply (WWAP, 2009). The role of hydro-dams in economic development has been well recognized (WCD, 2000 and Altinbilek, 2002). However, there are contested views on the social and environmental impacts of large dams in the Himalayan region (Bandyopadhyay, 2002). Despite the enormous HEP potential in the South Asian region, only 13.2% of the techno-economically feasible potential has been developed on a regional basis (SARI, 2013). Regional countries in the Himalayas have a huge share of HEP energy in their national energy supply, for example: Nepal (91.2%), Pakistan (37.1%) and India (25.1%) (Dharmadhikary, 2008). HEP production is supported by suitable physio-geographic conditions of the region. The middle and lower mountain region of the Himalayas has modest spatial and hydrological potential for the installation of HEP facilities. With this scenario, the HEP related hydrological ESs are set to grow across the IGB catchments.

An adequate supply of freshwater is essential in maintaining good agricultural production. Much of the accessible surface water is being utilized in croplands, so groundwater sources are now becoming the major alternative source of irrigation water in lowland plains (Shah, 2007). Groundwater requires a large amount of energy for extraction. In addition to agricultural production, a huge volume of water is also used (though not consumptive use) in food processing activities – before supplying agricultural products to consumers. Water and energy are thus closely interlinked with regional food security.

2.7.2 ESs approach for conservation and sustainable development

Hydrological ESs provisions of the upland areas are some of the most highly valuable ESs for local communities as well as millions of people in downstream basins. Although the region has received much attention in terms of ESs concept and its role in sustainable development, there is still a lack of rigorous studies about hydrological ESs at catchment scale (Pattanayak 2004). There is a major gap of detailed analysis of how different types of forest transitions affect low flows, and socio-hydrological links are inadequately studied (Lele, 2009). Despite the existence of a rich array of ESs, the mountainous region is economically underdeveloped and geo-environmental constraints impose severe limitations on the levels of resource productivity (Ives 2004).

The incentive-based landscape managements are under practice in different parts of the region (see, IUCN, 2006). Such practices are used to restore forest and landscape management in the upland areas. Some of them are direct payments or incentives while others are indirect rewards such as in-kind payments. Similarly, incentive-based watershed conservation programmes are used to ensure the quality of drinking water in certain parts of India (see, Kerr, 2002). Under the government's buffer zone management programme, Nepal has allocated 50 percent of its revenue to communities in the buffer zone (Spiteri and Nepal, 2005). These mechanisms are designed to achieve the twin goals of conservation and sustainable development at local level. More indirect but local level activities have been practiced in various parts of the region, for example, lodge operators and tourist agencies at the village of Syabrubensi in Nepal have agreed to transfer payments to local communities for the protection of 170,000 hectares of pristine silver fir and rhododendron forest in Langtang National Park (Landell-Mills and Porras, 2002). These are some of the initiatives that originated from awareness of ecosystem service functions.

Recently, the Rewarding Upland Poor for Environmental Services (RUPES) was a pioneering ESs based project primarily focused on assessing upland people's role on better management of watershed ESs and designing a framework for how to reward upland communities for their contribution (Van Noordwijk, 2005). The project was implemented in the Kulekhani catchment of the middle-mountainous region where the upland communities are volunteering watershed conservation through their participation in various activities which ultimately could improve hydrological ESs benefits to downstream beneficiaries.

At the regional scale, the Ecosystem Services and Poverty Alleviation Study in South Asia (ESPASSA) assessed the current situation of various ESs and their role in human well-being of the IGB regional countries. The ESPASSA has concluded that ESs are directly linked to poverty alleviation and achieving the Millennium Development Goals (MDGs) (ESPASSA, 2008). The findings also highlighted the change in ESs flow and its impact on the well-being of less affluent citizens. Parts of the IGB region have higher levels of poverty, especially in Nepal, Bangladesh and the eastern parts of the Indian states. So, any change in access to natural capital due to ESs policy may have wider impacts on individuals who depend on the available natural resources for their basic livelihoods. Similarly, the economic valuation of mountain specific ESs have been highlighted in the context of better conservation and sustainable use of available resources (Rasul et al., 2011). However, the challenge remains in terms of better understanding of biophysical production, distribution and consumption of ESs at appropriate spatial scales.

Rao and Pant (2001) highlighted a greater risk for conservation sustainability in the absence of continuing funding mechanisms, and indeed several conservation activities are already discontinued in the selected catchment. Governments (national and local) and local stakeholders have the responsibility to develop a funding mechanism that will allow the continuation of watershed conservation activities. In this situation, self-sustained and market based PES mechanisms can support upland communities in maintaining existing conservation achievements, enhance conservation activities and create livelihood opportunities.

2.7.3 The 'Virtual Water' concept for hydrological ESs policy

Water in the global trading system is known as 'Virtual water' (Allan, 1997). Freshwater use in agricultural commodities is the single most dominant virtual water supply that benefits distant beneficiaries (see, Allan, 1997; Oki and Kanae, 2004; Hoekstra and Hung, 2005; Chapagain and Hoekstra, 2008 and Allan 2011). On average, 3000 litres of water is required to produce the daily intake of food for a person (WWAP, 2006) which is significantly higher than that person's drinking water and other household requirement. Quantitative analysis of agricultural commodities shows the amount of water saved by importing countries is significant (Oki and

Kanae, 2004). It is particularly vital for water and food deficit countries. Thus, the virtual water concept of agricultural trade would become an active policy instrument to mitigate local and regional water scarcity.

In the IGB regional countries, the population growth is relatively higher than the world average (UNDP, 2011). To maintain the food security in the region, annual food production needs to be increased by 70% by 2050 (Nellemann and Kaltenborn, 2009). In that scenario, the use of agricultural water will continue to grow in the coming years. Rapid urbanization is also a major development across the region. Similarly, the regional countries have also experienced an unprecedented level of industrial growth and economic expansion. There will be a competing demand for more water supplies for these sectors. As a result, the value of agricultural commodities will be increased within and beyond the basins.

Agricultural products are exporting virtual water services to distant consumers via a series of intermediary traders, and those traders have been hugely benefited from the hydrological ESs of remote catchments (Chapagain and Hoekstra, 2008). Water supply companies, HEP authorities and water intensive industries (using catchment's water services for their production) are also exporting hydrological services to distant beneficiaries. Distant beneficiaries are not appropriately considered in ecosystem service decision making processes. The inclusion of those beneficiaries could make water resources policies more inclusive, equitable and sustainable.

2.8 Conclusions

The ecosystem services concept is now a powerful approach in managing natural resources through a detailed understanding of how they are produced, distributed and consumed in different geographical scales. Among others, water resources provide a range of ESs to people living in the proximity of water sources as well as for distant beneficiaries through the export of water embedded products. At the catchment scale, each hydrological ESs is directly related to water related attributes such as quantity, quality, location and the timing of water availability. Therefore, the detailed assessment of key hydrological attributes is crucial for the better understanding of hydrological ESs at different geographical scales.

A range of eco-hydrological processes (such as local climate, ET, environmental filtration and land and water management) directly or indirectly affect hydrological attributes and the related ecosystem services. In a human dominated catchment, freshwater resources are transformed into provisioning services such as crop ET services, HEP generation and domestic water supply. The land use and cover changes have considerable impacts on hydrological ESs through an alteration of the quantity and quality of water at the catchment scale. In addition, regional hydro-climatic features such as cloud water interception (fog water inputs) have a direct influence on water availability. Understanding these key elements at the appropriate spatial scale is essential and would support water resources based policies.

Agricultural water use accounts for more than 70% of human freshwater use, and it directly affects other hydrological ESs. A secured water supply to their croplands is essential for food security of the IGB regional countries. Thus, the modelling of crop ET scenarios using plausible cropland growth is essential for a better understanding of change in future water availability in the basin.

Freshwater resources also supply important ecosystem services not only within catchment boundaries but also beyond them. Water supplies to cities and HEP generation carry hydrological ESs to distant consumers at downstream and regional scales. Exporting agricultural commodities is one of the single most dominant virtual water supply systems that benefits distant beneficiaries across the world. While exporting agricultural products, they carry water services (embedded in crops) to distant consumers via intermediary traders. An appropriate inclusion of distant beneficiaries in the decision making process could make water based policies (such as the PES programmes) more inclusive, equitable and sustainable.

Various conservation activities, especially watershed protection programmes, are designed to improve the condition of hydrological ESs. They are mostly designed on an ad-hoc basis and need some detailed understanding of how conservation activities have changed the provision of hydrological ESs. Market based conservation approaches have been evolved in maintaining the hydrological ESs at catchment scale. However, the success of such schemes has yet to be explored in the context of watershed conservation as well as the improved hydrological services.

Chapter 3 Data and Methodology

3.1 An introduction to the methodological strategy

This research has applied a combination of research methods including spatially explicit hydrological modelling tools, relevant statistical methods and socio-ecological methods (such as field-based data collection, questionnaire survey, stakeholder interaction and policy level discussion) in order to assess hydrological ESs. We have chosen WaterWorld Policy support System (PSS) (see, Mulligan and Burke, 2005; Mulligan, 2010b; Bruijnzeel et al., 2011 and Mulligan, 2013b) and the Co$ting Nature Policy Support System (PSS) (Mulligan et al., 2010b and Co$tingNature-V2 2013a), both are process based and spatially explicit modelling tools to assess quantity and quality related hydrological attributes. In such a variable and heterogeneous environment as in the IGB catchments, the WaterWorld is capable of carrying out detailed and process based analysis of hydrological services. Alongside the WaterWorld, the Co$ting Nature tool is also used to assess some of the water provisioning services, relative conservation priority and relative impacts on water services including pressure and threats on water resources. We also applied socio-ecological methods particularly discourse-based analysis, questionnaire survey and focus group discussions at local level. Various Geographical Information Systems (GIS) such as ArcGIS, PCRaster and Global Mapper are also used to calculate and visualize biophysical, hydro-climatic and socio-economic parameters and result outputs.

The data and methods are designed to assess crop ET related hydrological ESs of the IGB catchments and water provisioning services of local catchments. Two selected mountain catchments are chosen for an in-depth understanding of freshwater ESs within the context of both historical and future plausible land use change scenarios. The study uses the SimTerra[2] database which consists of best available datasets of bio-physical, environmental and socio-economic properties available at 1km and 1ha spatial resolution from various remote sensing data sources (Mulligan, 2013a). Secondary data were also collected to improve the modelling database for local catchments.

[2] The 'SimTerra' database is a collection of world's best available database of hydro-climatic, biophysical and socio-economic properties available at 1km and 1ha spatial resolution. The database contains more than 400 environmental variables processed for quality, consistency and relevance. The database is produced by King's College London and Ambiotek

The hydrological modelling is focused on above ground hydrological fluxes such as precipitation (rainfall, fog input), ET and water balance. The WaterWorld model is also capable of estimating Cloud Water Interception (Fog Water Inputs). Water consumption in ET process is a key above ground hydrological flux which has vital role in water balance. Thus, we consider it as a major hydrological supporting ESs in crop production process.

The research is designed to assess crop related hydrological ESs of IGB catchments and key water provisioning services of local scale mountain catchments. Since the IGB catchments cover about 2.2 million km^2 area, 1km resolution of datasets are used to analyse entire catchments. At local scale, 1ha resolution of datasets are used to get more accurate modelling results for small sized catchments. The WaterWorld can model monthly datasets of mean precipitation, temperature, relative humidity, sea level pressure, wind direction and cloud frequency to quantify total hydrological inputs and outputs. The model calculates monthly and annual total average rainfall (wind-corrected), fog input, ET rates and the water balance. To calculate actual ET rates of different land cover types, the model requires net radiation, topography, and cloud frequency. Socio-economic datasets such as demographic distribution, population density and urban centres are also used by the model to better understand actual ES beneficiaries.

We then use the WaterWorld PSS to estimate the combined use of green water (soil moisture) and blue water (runoff and groundwater) services in croplands at the administrative region scale. We also examine water quality using WaterWorld's human footprint on water quality metric (Mulligan, 2013b) which assesses the impact of human footprints (including population, urbanization and protected areas) on the quality and quantity of freshwater services. We assume that the protected areas are strictly protected, the vegetation structure is intact and the human footprint is negligible. As a result, the water produced by the PA catchments may be pure relative to that produced by agricultural areas, but the quantity service of protected areas could be less than agricultural landscapes because of higher AET under forest cover. The research also assesses the impacts of human intervention especially land-use change (reforestation activities) on hydrological ESs of the selected catchments.

3.2 Rationale for spatially explicit quantitative assessment

Ecosystem services are distributed in complex ways in space and time so their true estimation can be better represented by spatially explicit assessment (see, Nelson et al., 2009; Nelson and Daily, 2010; Burkhard et al., 2012 and Crossman et al., 2013). Although the ESs concept has grown rapidly both in the science and policy arenas, the most of the spatial based methods are currently in their early stages of development. Due to dynamic and complex nature of some ESs provisions, it is always hard to quantify their values more accurately. Inconsistencies in methods challenge the development of robust values of ecosystem services in broader policy and natural resource decision-making process (Crossman et al., 2013). Troy and Wilson (2006) emphasised that spatially explicit units are necessary because supply and demand for ESs are distributed geographically. Thus, it is important to estimate hydrological ESs at appropriate spatial scale.

ESs assessment methods can be divided into two major categories. First, the broad-scale assessment of multiple services which extrapolate a few estimates of ES values based on major habitat types, to entire regions or the entire planet for example (Costanza et al., 1997; Troy and Wilson, 2006; MA, 2005 and Rockström et al. 1999). Such broad scale assessment of ecosystem services may have incorrectly assumed that every piece of land has equal value of assessed services (regardless of their variability in biophysical properties quality, rarity, spatial configuration, size, proximity to population centres or the prevailing social practices and values) (Nelson et al., 2009). Second, local scale ESs assessment is usually focused on a single service in a small area where researchers carefully model the ecological production function to determine how provision of that service depends on local ecological variables (for e.g., Ricketts et al., 2004). Some of these production function approaches also use market prices and non-market valuation methods to estimate the economic value of the services and how that value changes under different ecological conditions (Nelson et al., 2009). Using plausible scenarios for land use change may help to understand the changing prospects of services in the most likely management conditions (see, Nelson et al., 2009; Nelson and Daily, 2010 and Pandeya and Mulligan, 2013). Although these methods are superior to the broad scale assessment, such studies may lack both the scope (the number of services) and the scale (geographical and temporal) to be relevant for most decision making processes.

To integrate ESs concept into policy level, a combined approach of both small-scale rigorous analysis and the broad scale assessment is essential (see, Jackson et al., 2005; Naidoo and Ricketts, 2006 and Egoh et al., 2008). Quantifying ecosystem services in a spatially explicit manner, and analysing trade-offs between them can help to make natural resource decisions more effective, efficient and defensible (Nelson et al., 2009). Selected catchments represent the middle mountainous region of the Himalayas, and a detailed assessment would improve the scientific knowledge of some hydrological ESs of the region.

The value of ecosystem services also relies on their use and distribution at different geographical scales from local, regional and global level. That makes the quantitative assessment of certain services more complex (Nelson et al., 2009). Water related services such as HEP energy and agricultural goods are distributed not only within the catchment but also far beyond of it. Thus, the need of spatially explicit and quantitative hydrological modelling tools are truly relevant for the selected research sites for better understanding of available water related ESs and their likely changes in future under certain plausible scenarios.

3.3 The selection of hydrological modelling tools

In recent years, a range of methodological approaches have been developed to understand various hydrological ESs (see, Mulligan et al., 2010a and Bagstad et al., 2013). There are several spatially explicit hydrological modelling tools such as Artificial Intelligence for Ecosystem Services (ARIES) model (see, Villa et al., 2009; Bagstad et al., 2011 and Villa et al., 2011), Integrated valuation of Ecosystem Services and Trade-offs (InVEST) model (see, Tallis and Polasky, 2009; Daily et al., 2009; Nelson et al., 2009; Kareiva et al., 2011 and Tallis et al. 2013), Soil and Water Assessment Tool (SWAT) model (see, Neitsch et al., 2009 and Winchell et al., 2010) and the WaterWorld & Co$ting Nature models (Mulligan and Burke, 2005; Bruijnzeel et al., 2011 and Mulligan, 2013b). We assessed various hydrological modelling tools in order to identify the best models for the research. The brief assessment of selected ESs models is presented in table 3.1, below.

Table 3-1: A brief assessment of major ESs modelling tools and their key features

ESs modelling tools and references	Brief description
Ecosystem Services Review (ESR),http://www.wri.org/ (WRI, 2012)	Publicly available, spread sheet-based process to qualitatively assess ecosystem services impacts A

ESs modelling tools and references	Brief description
	well-documented approach to quickly describe ecosystem services and impacts qualitatively, only useful for corporate level ES assessment
Artificial Intelligence for Ecosystem Services (ARIES),http://www.ariesonline.org (Villa et al., 2009; Bagstad et al., 2011 and Villa et al., 2011)	Open source modelling framework to map ecosystem service flows; online interface and stand-alone web tools under development. Data and models available for several western U.S. states; global model and online interface under development would enable widespread use
The WaterWorld Policy Support System (PSS) (http://www.policysupport.org/waterworld (Mulligan and Burke, 2005; Bruijnzeel et al., 2011 and Mulligan, 2013b)	Web-accessible tool to estimate hydrological ESs, detailed process-based modelling of water quantity, quality and some regulation ESs, can be independently apply anywhere in the world, best suited for data poor and problem rich environments, well-documented, data provided by the Global SimTerra database at 1 km and 1 ha resolution, available ground data can be used, can apply scenarios for LUCC and climate change, policy options/interventions tools for land and water management, Also includes FESTA (Fog Interception for the Enhancement of Streamflow in Tropical Areas) model to quantify fog inputs (cloud water interception) in total annual precipitation
Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), http://www.naturalcapitalproject.org, (Tallis and Polasky, 2009; Daily et al., 2009; Kareiva et al., 2011 and Tallis et al., 2013)	Open source ecosystem service mapping and valuation models accessed through ArcGIS, limited data availability, well-documented, can be independently applied and tested, amenable to widespread use, able to model quantity and quality related hydrological ESs, scenario modelling for climate change and LUCC scenarios.
Multi scale Integrated Models of Ecosystem Services (MIMES),http://www.afordablefutures.org (Boumans and Costanza, 2007)	Open source dynamic modelling system for mapping and valuing ecosystem services. Requires commercial modelling software; model construction currently requires contracting with development group
The Co$ting Nature, http://www.policysupport.org/costingnature (Mulligan et al., 2010b and Co$tingNature-V2, 2013a)	Web-accessible tool to map ecosystem services and conservation priority indices. Data and model are accessible for the assessment of ecosystem services (both realized and potential services), conservation priority, human footprints, current pressures and future threats of any region in the world, readily available. Policy relevant approach.

ESs modelling tools and references	Brief description
Social Values for Ecosystem Services (SolVES),http://solves.cr.usgs.gov (Sher rouse et al., 2011)	ArcGIS toolbar for mapping social values for ecosystem services based on survey data or value transfer. No survey data available; conditions at study site too different from past studies to support value transfer
Ecosystem Portfolio Model (EPM), http://geography.wr.usgs.gov (Labiosa et al., 2013)	Web-accessible tool to model economic, environmental, and quality of life impacts of alternative land-use choices. Developed for adjacent Santa Cruz River watershed but; infeasible to run for new sites without a substantial external research effort
Natural Assets Information System (NAIS), http://www.sig-gis.com (Troy and Wilson, 2006)	Proprietary valuation database paired with GIS mapping of land-cover types for point transfer. Proprietary method; limited primary valuation studies to support application to study site
SWAT (swat.tamu.edu) (Neitsch et al., 2009 and Winchell et al., 2010)	Physically based model, can be used to assess water demand and allocation, requires detailed data for the additional software and GIS capacity to assess the results,
Water Evaluation and Planning System (WEAP) (http://www.weap21.org/) (Yates et al., 2005 and Sieber and Purkey, 2007)	Can be applied at multiple scale from small watershed to large basins, limited physical processes for scenario analysis, substantial input data required to model water related ES

(Source: Mulligan et al., 2010a and Bagstad et al., 2013)

Several integrated assessment methods are also available such as the Toolkit for Ecosystem Services Site-based Assessment (TESSA) tool (Peh et al., 2013), three distinct but complementary methods (habitats perspective, service perspective and place-based perspective) for country level ESs assessment (Haines-Young and Potschin, 2008) and integrated valuation of ESs and their trade-offs (Daily et al., 2009; Kareiva et al., 2011 and Tallis et al., 2013). Since the research is quantifying the changes in key hydrological attributes, the research requires processed based spatial modelling tools to assess the marginal changes in hydrological attributes.

The selection of spatially explicit modelling tools primarily depends on study aim/objectives, data availability, the types of ESs and any specific research or policy question to be addressed. The scenario modelling is also an important part of this research for the better understanding of future prospect of selected hydrological ESs.

While considering these issues, this research has chosen the WaterWorld and the Co$ting Nature tools as they are appropriate to the types of analyses carried out here. Since the research is exclusively focused on water related ESs, the process based model is essential to understand the marginal change in hydrological attributes. Both models are provided with the best available and high resolution datasets which makes application rapid and easy and the models can be used to assess an ESs baseline but also to apply various plausible scenarios.

3.4 Modelling of land use change scenarios

Scenario modelling is a widely used practice for the better understanding of hydrological ESs within the context of Land Use and Cover Change (LUCC) scenarios (see, Kepner et al., 2004; Viney et al., 2009 and Nelson et al., 2009). LUCC is one of the major factors that disrupt the hydrological cycle and alters the balance between rainfall and evapotranspiration and the runoff response of the catchment (Foley et al., 2005). Human dominated landscapes with extensive land use change have a strong impact on the water balance of river catchments (DeFries and Eshleman, 2004). Several studies have assessed the effects of land use change on hydrological fluxes in river basins by paired catchment studies (Bosch and Hewlett, 1982 and Brown et al., 2005) or single model applications (see, Sahin and Hall, 1996 and Costa et al., 2003). Although many studies have found that the resulting impact of land use change especially deforestation in semi-arid regions has a positive impact on water balance (Sahin and Hall, 1996 and Costa et al., 2003) but some studies from the tropical region do not find the same relationships (see; (Bruijnzeel, 1990; Bruijnzeel et al., 2006; Bruijnzeel et al. 2011 and Sáenz and Mulligan 2013). Quantitative assessment of hydrological fluxes in changing land use systems requires the use of hydrological catchment models which have been validated for the regional and local scale hydrological modelling in different environmental conditions.

Scenario modelling is widely used for the better understanding of the current status and future trends of hydrological ESs although it is important to note that no scenario will match the future as it actually occurs. The Millennium Ecosystem Assessment (MA, 2005b) has used four different scenarios such as Global Orchestration (based on the global trade and economic liberalization), Order from Strength (concerned with security and protection), Adapting Mosaic (strengthening local ecosystem management strategies) and TechnoGarden (relying on environmentally sound technologies) to explore the plausible futures of ecosystems and human well-being.

Since this research focuses on both regional and local scale hydrological assessment, we have developed different plausible scenarios considering the regional and local conditions. For the Indo-Gangetic basin, we have developed cropland expansion scenario using IWMI and FAO studies on predicted cropland expansion by the year 2050. The research has designed a plausible LUCC scenario in which more cropland growth is expected. Using this scenario, the WaterWorld model assesses the change in water balance at regional administrative scale. The details of a plausible scenario are explained in the methodological section of the chapter 4. Similarly, for the selected mountain catchments in the middle mountainous region of the Himalayas, the plausible land use change scenarios have been developed based on catchment scale studies, site observation and our best assumptions on how land use will change in coming decades. For the Kulekhani catchment, the scenarios are developed using 'Adapting Mosaic[3]' scenario in which local scale management programmes are decided based on the locally adapted sustainability approach. The scenario developed for the SNNP catchment represents the 'Order from the Strength[4]' in which the outcomes are determined by the protection through boundaries and in an alternative scenario, the PA falls into the more integrated watershed management concept. The explanation of the LUCC scenarios for the Kulekhani and the SNNP catchments is provided in chapter 5 and 6, respectively.

3.5 Study area delineation

We have delineated the entire IGB catchment for the crop ET related hydrological ESs assessment. Using PCRaster modelling framework, figure 3.1 is developed which shows the HydroSHEDS DEM of the IGB catchment at 1km spatial resolution (Lehner et al., 2008). It shows the geographical location of the Himalayas and the Indus and Ganges basins plus two selected catchments in the lower mountainous region of the Central Himalayas. Altitudinal variation of the entire catchment ranges

[3] The 'Adapting Mosaic' scenarios are designed based on the principles that lead to approaches that favours experimentation and local control of ecosystem management (MEA, 2005a)

[4] The 'Order of the Strength' scenarios examines the outcomes in which strict protection measures are adopted to enhance the conditions of ecosystem services inside the boundaries (MEA, 2005a)

from the mean sea level to the top of the Mount Everest, the world's highest mountain. Upstream regions are represented by the lower to middle and higher mountainous regions of the Himalayas. Downstream regions are occupied by the vast scale of Indus and Ganges plains.

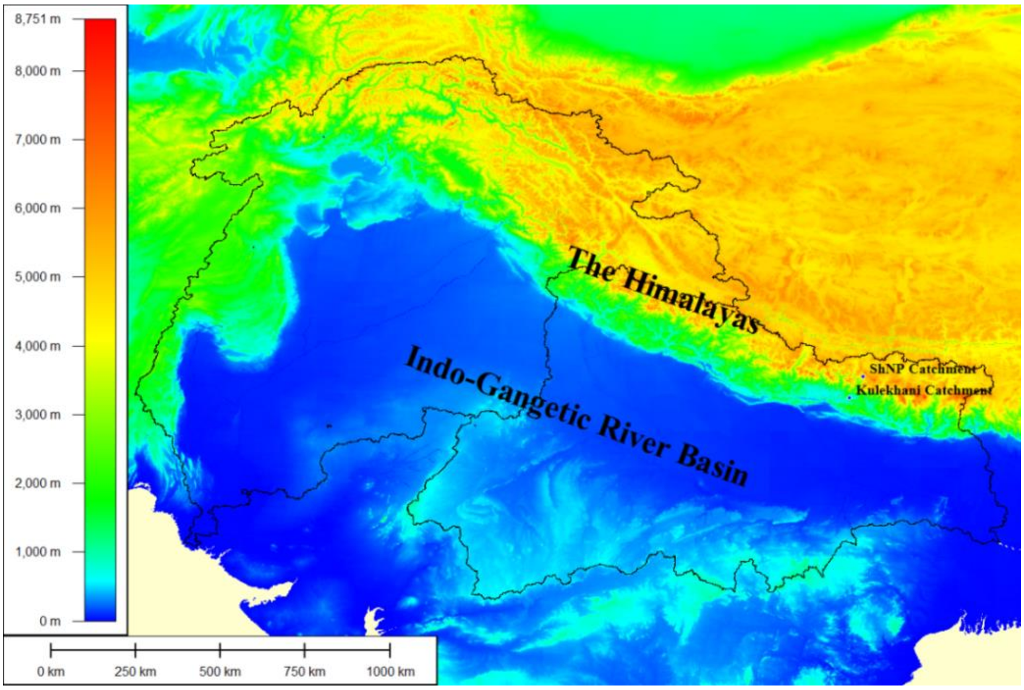


Figure 3-1: An overview of geographical locale of IGB region and selected catchments (Lehner et al., 2008)

While delineating the regional catchment, the study uses 1 km spatial resolution DEM based on the SRTM, and for the selected catchments which are smaller in size, uses 1 ha (90 m) spatial resolution also based on the SRTM (Lehner et al., 2008). The regional scale study area is chosen for the crop ET related hydrological ESs assessment of the entire IGB catchment. And, local catchments are selected for the drinking water and HEP related hydrological ESs.

The research has identified two selected mountain catchments for the detailed assessment of hydrological ESs. Several criteria such as types of hydrological ESs, conservation approaches and land use change are considered while selecting them. On the one hand, the SNNP catchment is supplying drinking water supply as a major hydrological ESs, on the other hand, the Kulekhani catchment is providing HEP related ESs. Both catchments have experienced different sets of human interventions over the last three to four decades. Table 3.2 presents some salient features of the selected catchments.

Table 3-2: Salient features of selected mountain catchments

Characteristics	Shivapuri Nagarjun Protected Area	Kulekhani Catchment
Size	159 km^2	125 km^2
Location	Latitude ($27^0$44'N to $27^0$51'N) and Longitude ($85^0$14'E to $85^0$30'E)	Latitude ($27^0$34'N to $27^0$42'N) and Longitude ($85^0$01'E to $85^0$12'E)
Elevation range	1530 masl to 2606 masl	1320 masl to 2732 masl
Conservation practice	National Park – strictly protected under the National Park rules and regulations	Watershed management activities and community based forestry programme
Human Interference	Mostly uninhabited except for two villages in a sub-catchment (i.e. Sundarijal area) where about 1,700 upland people live within the park	More than 44,000 people in the catchment, mostly relied on agricultural based subsistence livelihoods
Major hydrological ecosystem services	Available water is primarily used for drinking water supply in Kathmandu valley and generating HEP from a sub-catchment	Available water is collected in a man-made reservoir for HEP generation

Both catchments are located in the middle mountainous region of the central Himalayan region and the proximity of densely populated Kathmandu valley (Fig. 3.2, below). The map also shows the surrounding administrative areas which are primary beneficiaries of hydrological ES of the selected catchments. However, the diversion of available water resources makes the catchments more important for the hydrological ES to distant beneficiaries.

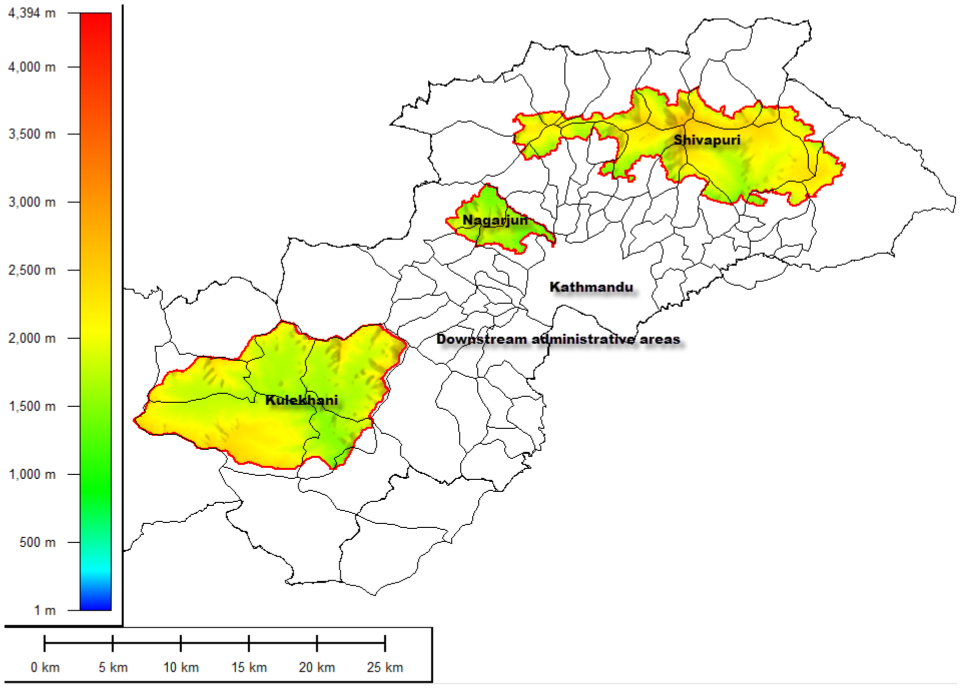


Figure 3-2: Selected mountain catchments and surrounding downstream areas

The SNNP catchment is located in the northern part of the Kathmandu valley from where a major river (the Bagmati) originates. Similarly, the Kulekhani catchment is also located in same mountainous range. The selection of these catchments is based on their supply of hydrological ESs to downstream as well as distance beneficiaries. While the SNNP catchment is supplying drinking water supply to downstream urban centres in Kathmandu valley, the Kulekhani catchment is producing HEP services for the entire country (as it is distributed through the national grid system). Both catchments have different sets of conservation interventions. The SNNP is implementing PA based conservation programme whereas the Kulekhani catchment has been experiencing a number of watershed conservation interventions supported by local communities. Thus, the selection of mountain catchments represents the major types of hydrological ESs as well as two extensively used conservation approaches in the region.

3.6 Data acquisition and development

3.6.1 Data requirements

A wide range of possible datasets of hydro-climatic, biophysical and socio-economic properties are required for the intended hydrological ESs modelling. The list of static data requirements includes HydroSHEDS DEM, local drainage direction and land cover maps. Dynamic datasets include precipitation, relative humidity, cloud frequency, wind speed/direction and incoming short-wave radiation. Datasets related to socio-economics include demography and urban areas.

The study also requires ground-based, locally collected datasets for the selected catchments that include input datasets related to water supply, crop production, and HEP projects. Local hydro-climatic datasets are also used to improve and validate the SimTerra database. Similarly, datasets related to land use change and conservation programmes will be required to assess the conservation impact on hydrological ESs generation. Available local data would also help to understand the level of human influence on key hydrological ESs.

3.6.2 Spatial and temporal scale

The study has used a grid cell representation with a spatial resolution of 1 km for the IGB catchment and 1 ha (90 m) for the selected catchments. Available datasets are in un-projected geographic coordinates and use the WGS84 datum. The temporal scale of the SimTerra datasets is varied for different variables and mostly available in monthly, yearly and seasonal scale. Most spatial datasets are available up to year 2000 (circa), for example, 'WorldCLIM' hydro-climatic datasets are available as a mean climatology for the period 1950 to 2000. Primary datasets from the fieldwork have different spatial and temporal scales. Fieldwork was primarily focused on improving input datasets used for the modelling of freshwater ESs provided by the selected catchments. We have collected rainfall and water discharge data from the hydro-climatic data stations in and around the selected catchments.

The rainfall datasets for the two sites have been averaged based on the ground datasets for available periods. For the Kulekhani catchment, the study has collected from 3 hydro-meteorology stations located within and close proximity of the catchment for the 31 years of mean monthly datasets from the 1980 to 2010. And for the Sundarijal sub-catchment of the SNNP, the precipitation data was available from a station for the 16 years (between 1994 and 2010). Thus, the temporal datasets of available ground rainfall for the selected local catchment are different in scale. The monthly average data of ground rainfall from the collected sites are used in the system through data parameterization (recalculation) process.

3.6.3 The SimTerra database

The SimTerra database is the primary source of all major spatial datasets of biophysical, hydro-climatic and environmental properties which is currently available at 1 km or finer resolution for the modelling of hydrological ecosystem service, crop production and socio-economic processes including for development of scenario-analysis for climate, land use and economic changes (Mulligan, 2013b). The database is built up from a wide range of the best available global datasets. The data have been generated or sourced from a ground-based and remote sensing source. Major datasets used for the modelling of hydrological ecosystem services are WorldClim climatology (Hijmans et al., 2005), wind speed (New et al., 2002), cloud climatology (Mulligan, 2006b), SRTM terrain (Farr and Kobrick, 2001), and land cover from Landsat-based vegetation continuous fields (Sexton et al., 2013). Table 3.3 shows the key datasets available in the SimTerra database and used for the hydrological modelling carried out here.

Table 3-3: Major spatial datasets used in WaterWorld (Source; Mulligan, 2013a)

Variable	Unit	Source
Mean precipitation (monthly)	mm/month	(Hijmans et al. 2005)
Total precipitation (annual)	mm/yr	(Hijmans et al., 2005)
Mean temperature (monthly)	deg. C	(Hijmans et al., 2005)
Mean temperature (annual)	deg. C	(Hijmans et al., 2005)
Mean daily maximum temperature (monthly)	deg. C*10	(Hijmans et al., 2005)
Mean daily minimum temperature (monthly)	Deg. C*10	(Hijmans et al., 2005)
HydroSHEDS DEM	masl	(Lehner et al., 2008)
Elevation (SRTM1k)	masl	(Farr and Kobrick 2001)
Local Drainage Direction (LDD)	direction	(Mulligan, 2013a)
Monthly relative humidity (monthly)	%	(New et al. 2002)
Air temperature (monthly)	deg. C	(New et al., 2003)
Wind speed (monthly)	m/s*10	(New et al., 2003)
Boundary layer wind direction (monthly)	degrees from N	(BADC 2004)
Mean sea level pressure (monthly)	mb	(BADC, 2004)
Cloud frequency (DJF)	fraction	(Mulligan 2006b)

Cloud frequency (MAM)	fraction	(Mulligan, 2006b)
Cloud frequency (JJA)	fraction	(Mulligan, 2006b)
Cloud frequency (SON)	fraction	(Mulligan, 2006b)
Cloud frequency (monthly)	fraction	(Mulligan, 2006b)
Mean cloud frequency (annual)	fraction	(Mulligan, 2006b)
Cloud frequency (00:00-6:00) hrs	fraction	(Mulligan, 2006b)
Cloud frequency (06:00-12:00) hrs	fraction	(Mulligan, 2006b)
Cloud frequency (12:00-18:00) hrs	fraction	(Mulligan, 2006b)
Cloud frequency (18:00-24:00) hrs	fraction	(Mulligan, 2006b)
TRMM rainfall	mm/yr	(Mulligan 2006a)
Protected Areas		(WDPA 2012)
Important Bird Areas		(Birdlife International, 2012)
Landsat Land cover	%	(Sexton et al. 2013)
Vegetation coverage (tree)	%	(Hansen et al. 2006)
Vegetation coverage (herb)	%	(Hansen et al., 2006)
Vegetation coverage (bare)	%	(Hansen et al., 2006)
Croplands 2000	Fraction	(Ramankutty et al, 2008)
Agricultural land coverage including cereals crop fraction	Fraction	(Monfreda et al. 2008)
Urban centres		(CIESIN 2008)

The SimTerra database currently consists of more than 400 different maps for nearly 200 different variables. The database supplies the core input datasets to run the WaterWorld model for hydrological ES modelling. The database includes some new datasets such as global dams database and some reprocessed datasets such as globcover maps of land use, vegetation cover, snow and ice cover, water and urban fractions.

The research has two spatial scales of hydrological ESs modelling i.e. regional scale of IGB catchment and local scale of two mountain catchments. For the IGB scale crop ET assessment, the study has used global scale datasets at 1 square km resolution available from the SimTerra database. Key datasets required for the modelling include the HydroSHEDS DEM (Lehner et al., 2008), WorldClim hydro-climatic data (Hijmans et al., 2005), Cropland2000 (Ramankutty et al., 2008), vegetation cover (Hansen et al., 2006) and cloud frequency (Mulligan, 2006b). For the local catchment scale modelling, some datasets are collected at this native resolution (for example, the SRTM DEM and Landsat-derived land cover but some datasets have been downscaled from coarser resolution data using bilinear interpolation so they can be used as 1 hectare spatial resolution. In addition, some key datasets such as rainfall and locally specific land cover (including wetland) maps have been parameterized based on the ground data and field observation.

3.6.4 Topography and land cover

Topographic datasets have a fundamental role in hydrological ESs modelling. The SRTM DEM is available at a 1 km continuous raster dataset, where the individual cell corresponds to elevation expressed in metres above sea level (Farr and Kobrick, 2001). The accuracy of a DEM depends on spatial resolution and the data generation process. For the selected catchments, 1 ha (90 m) spatial resolution SRTM-DEM (processed by CGIAR) was used. It has greater accuracy compared to standard DEMs for slope gradients greater than 10^0 (Gorokhovich and Voustianiouk, 2006).

In spatially distributed hydrological modelling, DEMs are used to extract information about slope, aspect and drainage networks. The spatial details as well as horizontal and vertical accuracy of the datasets have a critical role in the overall realism of hydrological modelling processes, in particular the determination of flow paths through the Local Drainage Direction (LDD) network (Lehner et al., 2008).

The SimTerra database has compiled land cover datasets from recently available global data sources such as bare land, herb, shrub and tree coverage from MODIS VCF (Hansen et al., 2006). For the local catchments, the study has used 30-m resolution dataset of percent tree cover by rescaling the 250-m MODIS VCF Tree Cover layer using circa-2000 and 2005 Landsat images (Sexton et al., 2013). Missing landcover types such as reservoir, human settlements and road networks of the Kulekhani catchment are digitized using Google Earth V.06 (DigitalGlobe, 2013).

3.6.5 Climate and hydrology

The SimTerra database has compiled climatic datasets of about 1 km spatial resolution from the ‘WorldClim’ database that covers monthly precipitation and mean, minimum and maximum temperature of the world's land surface (excluding Antarctica) for the 1950 to 2000 period (Hijmans et al., 2005). Although the

WorldClim datasets may have some uncertainties in highly mountainous as well as poorly sampled areas, the database is widely considered as the most reliable dataset available for the hydrological modelling to be carried out here (Mulligan, 2013a). WorldClim temperature and rainfall are used as inputs to WaterWorld. The SimTerra database has also compiled a set of high resolution climatic datasets such as air temperature, wind speed and relative humidity of surface climate over global land areas (New et al., 2002).

Cloud related datasets derived from the MODIS MOD35 Cloud Mask Product and provided by King's College London (Mulligan, 2006b) are used by WaterWorld to modulate modelled top of the atmosphere solar radiation. The entire archive (2001-2006) of tropical MOD35 data was analysed to derive annual average, monthly and diurnal statistics on cloud frequency at 1km resolution for the entire tropics.

3.6.6 Rainfall (TRMM)

An alternative to WorldClim, a satellite derived rainfall climatology is also available. This is derived from a rainfall climatology based on analysis of the full dataset for TRMM 2B31 (combined PR-Precipitation Radar, TMI-TRMM Microwave Imager) Rainfall Profile Product from 1997-2006 and available at 1km spatial resolution (Mulligan, 2006a). The climatology has been calculated as mean of all rainfall observations to March 2006 with the TRMM 2b31 product and represents atmospheric rainfall. Approximately 50,000 satellite swaths (0.5 TB of data) were processed to produce these grids. For the selected mountain catchments, the research has collected ground datasets (see, in chapter 5, and 6, below) which have been used to modify the WorldClim datasets.

3.6.7 Fieldwork and ground data collection

To assess hydrological ESs of selected mountain catchments, we require local data and information related to production, supply and use. People's perception on key hydrological ESs is also useful to validate modelling results and to understand the trend of major hydrological ESs. Discussion at policy level helps to understand how conservation activities are being implemented over the years. Local hydrological data such as rainfall and discharge were also collected from available sources to improve the modelling datasets. Secondary data and information of freshwater ecosystem services were collected from all available sources such as water supply company, electricity authority and park authority. Reports relevant to all types of water use such as water supply and HEP generation were collected.

We also organized stakeholder engagements at expert/policy level and community level to obtain deeper insight into water resources and their use in different sectors. Workshops/seminars and meetings were held in the selected catchments to inform hydrological ESs of these catchments and receive feedback. The description of fieldwork activities for both catchments is described in section 3.7.2 and 3.7.3 below.

3.6.8 Limitations of data

The Himalayan region of the IGB catchment has a dearth of spatial hydro-climatic and biophysical data and has very few and largely short term ground-based monitoring stations (Kattelmann 1987). Long-term site specific climatic records are not consistently available for the region. Precipitation gauges are poorly representative due to extreme topographic variability in rainfall for example rainfall records at the valley bottom are considerably lower compare to surrounding peaks (Higuchi et al. 1982, Winiger et al. 2005). Similarly, data related to sub-surface water storage and dynamics are not currently available in the SimTerra database. Lack of long-term hydrological records and practical difficulties in maintaining data quality of the records are also major uncertainties in hydrological data management practices in the region. Thus, the modelling results should be interpreted with regional and local contexts.

3.7 Methodological approach for individual research objectives

3.7.1 Modelling crop ET and its potential impact on future water availability

The research has applied the WaterWorld model to assess crop ET related hydrological services of the IGB catchments. A detailed methodology is explained in chapter 4 (in a peer reviewed paper). The research has applied some innovative approaches including administrative region scale assessment and developing future cropland growth scenario based on FAO and IWMI studies.

3.7.2 Assessing water provisioning services of a Protected Area catchment

The research has applied an integrated approach to quantify the available hydrological ESs of the park catchment (in chapter 5). The methodological framework of this study includes application of an advanced hydrological modelling tool (i.e. the WaterWorld) and a set of different socio-ecological approaches such as questionnaire surveys, key informant interviews and stakeholder discussions to assess the available hydrological ecosystem services. Fieldwork was also carried out to collect available hydro-climatic datasets and secondary information from different sources. Research collaboration was developed with Cambridge Conservation Initiative, Birdlife International, Bird Conservation Nepal, Park Authority and relevant government departments to conduct field work and collect required data sets. Research findings from the joint work have already been published (see, Peh et al., 2013 and Birch et al., In press). Our contribution was focused about the use of WaterWorld model in TESSA toolkit and assessing key hydrological ESs using plausible scenarios in Phulchoki mountain forest, respectively.

Field analysis of hydrological ESs requires sophisticated instrumentation, long-term data collection and detailed analysis, in order to account for climate variability and any progressive change in soil and vegetation that might occur after land use change and have impacts on hydrological fluxes. Where this is not possible, process-based modelling can be used to understand the hydrological baseline and the impacts of land use change by combining knowledge of hydrological processes with locally-specific data on climate, terrain and vegetation (for example, see, Mulligan, 2010; Bruijnzeel et al. 2011, Peh et al., 2013 and Birch et al, In press). Thus, the selection of the WaterWorld model is relevant to the objective set for the catchment.

Modelling of hydrological ESs involves understanding of the hydro-climatic and bio-physical processes of the catchment. These include the annual and inter-annual rainfall patterns, wind direction and velocity, temperature, cloud frequency, cloud water interception and vegetation coverage. Then, it is crucial to estimate the major hydrological fluxes such as rainfall and cloud water deposition/impaction and water outputs such as actual evapotranspiration of the area, ground water recharge and the diversion of water resources for various uses.

Hydrological fluxes are not the same as hydrological ESs. It is therefore important to understand the people’s use of freshwater and their perception of freshwater ecosystem services. The study has carried out following key activities to acquire and improve upon relevant datasets and thus help provide a better understanding of freshwater ESs of selected catchment. Secondary data were collected from all available sources such as the Water Supply Company, national park and private research institutions. Hydrological data such as rainfall, river discharge were also collected from available sources.

We have selected Sundarijal sub-catchment for a detailed assessment of hydrological ESs using plausible land use scenarios. Since this study is quantifying hydrological ESs of a local catchment, ground based datasets include available rainfall and river discharge. Land use change related datasets are also essential to understand the current and future scenarios and such data were collected from the government institutions such as park authority and forest department. Water supply data is collected from the Kathmandu Upathyaka Khanepani Limited (KUKL), a major water supply company in Kathmandu.

It is important to know local people's perception on hydrological ESs and how they experience conservation activities and their influence on hydrological ESs. A total of 52 questionnaire interviews (25 female and 27 male interviewers) were sampled in Sundarijal sub-catchments and the buffer zone areas of the PA. Major respondent groups include 35 farmers, 10 businessmen and the rest from job holders. Similarly, 45 respondents were born locally and 7 were migrants came from outside the region. The survey was designed as a qualitative assessment to understand the people's understanding on their water resources uses, watershed conservation impacts and any change in water related ESs. The questionnaire is broadly divided into two main parts, first concerning the general information about the respondent and the rest of the questionnaire is divided into five key questions such as i) source, use and importance of freshwater at local level, ii) Freshwater quantity and seasonal use, iii) any payment mechanism for water consumption, iv) land use change and resulting impacts on watershed ESs, and v) understanding the water services of the catchment. A sample questionnaire is attached in Appendix I. The survey was also useful to help validate modelling results.

The research has also applied key informant interviews and discussions with local people and park officials to understand the change in land use and land cover in recent decades. Such discussions were hugely useful to understand the forest regeneration activities in the catchment. Stakeholder engagements at expert/policy making level and community level were also conducted to gain insights on policy relevant issues of the PA-led conservation activities. Focus group discussions were also held to inform stakeholders of our hydrological ESs assessment of the catchment and receive user feedback.

3.7.3 Assessing hydrological ESs and the long-term prospect of a PES programme in a human dominated catchment

The research applied a combination of advanced hydrological modelling tools (i.e. The WaterWorld PSS), GIS applications (ArcGIS, global mapper, PCRaster GIS) and secondary data sources to assess the hydrological ecosystem services of the human dominated Kulekhani catchment. The WaterWorld PSS consists of a suite of models that can use current and scenario land cover to estimate ecosystem services using biophysical relationships between land cover properties and hydrological ecosystem services (Mulligan 2013). The model can produce various hydrological ESs such as quantity related services (water provision for human uses) and water quality services (sedimentation/siltation processes). As any model outcome, the results are sensitive to data quality and availability and an understanding of hydrological and bio-physical characteristics as well as land use dynamics (Mulligan, 2013b).

The WaterWorld model is applied at 1ha spatial resolution to estimate hydrological ecosystem services of both Kulekhani catchment and the SNNP catchment. First, the study has assessed the spatial distribution of major hydrological fluxes such as wind driven rainfall, fog inputs, AET losses and thus water balance at the catchment scale. The study has also modelled hydrological regulatory ESs of the catchment. To understand the future change in hydrological ESs, the study has used a future plausible scenario in which forest cover would increase in next three decades. To model fog water input, information is required on i) the spatial extent of ground-level cloud (i.e. fog), ii) the type of vegetation present (trees vs shorter herbaceous vegetation), iii) the magnitude and variability of vertical and lateral fog fluxes (i.e. deposition and impaction), and iv) the cloud water interception efficiency of the vegetation present. Total fog input is calculated as the fog flux carried by the wind and either impacted or deposited on the vegetative leaf area (Mulligan and Burke, 2005).

For the better modelling outcomes, the study improved the Simterra database with available ground datasets. Average monthly and annual rainfall data of the study catchment is developed by multiplying fractional differences between ground datasets at Palung, Markhu and Thankkot stations to the WorldClim hydro-climatic data downscaled to 1 ha using bilinear interpolation from the 1km grid. The temporal scale of available datasets vary, for e.g., the spatial dataset for hydro-climatic data (available from the ‘WorldCLIM’ database) represents a 50 year mean climatology (from 1950 to 2000) whereas ground-based rainfall datasets represents 30 years of datasets between 1980 and 2010.

Key ground-based datasets collected are rainfall, forest cover and reservoir sedimentation level. Socio-ecological methods such as Discussions with local communities and experts helped to better understand land use dynamics in the catchment and the role of ecosystem services in livelihoods. Field visits were also useful to gather views for the development of future plausible land use scenarios. Watershed conservation and forest management related data were collected from the Department of Soil Conservation and Watershed Management (DSCWM) and Department of Forestry (DOF), respectively. Similarly, hydrological data were available from the department of hydrology and meteorology (DHM) and Nepal Electricity Authority (NEA). Reports relevant to land use and land cover change were collected from past projects including the Bagmati Integrated Watershed Management Project (BIWMP) and the community forestry management programme. Sedimentation level in the reservoir is an indicator that shows the soil loss trends and the loss of reservoir capacity for HEP generation and these data were collected from the HEP operation company.

The research also assessed the prospect of existing PES programme based on the available secondary data and information. In addition, I was closely involved during the implementation of the PES scheme, so detailed understanding of local issues were hugely important while assessing the long-term success of the programme. Although the chapter is trying to link the modelling of hydrological ESs to the success of land cover improvement (supported by upland communities through community forestry programme), the success of PES scheme is multifaceted and dependent on various local and institutional issues. Thus, the interpretation of PES programmes must be understood in the context of local realities.

3.8 Model specifications

3.8.1 The WaterWorld Policy Support System

The WaterWorld Policy Support System (PSS) is a spatially explicit, process-based, data intensive and self-parameterized hydrological model to estimate water balance and to assess various hydrological ES (Mulligan 2013b). The model is provided with global SimTerra database, and can estimate baseline hydrological fluxes representing the mean water balance for 1950-2000. Simulations are possible at 1-hectare resolution for tiles with dimensions of one degree of latitude and longitude or at 1-square km resolution for 10 degree tiles. Results are provided visually and as GIS files for download and further analysis. The WaterWorld model is designed to perform scenario-based analysis for hydrological ESs assessment, water productivity and food and environmental security in the region (Mulligan and Burke, 2005; Bruijnzeel et al., 2011 and Mulligan, 2013b). The model also allows users to assess the impact of climate change scenarios or to evaluate the impact of land cover change or land management interventions for better policy options.

The model is provided with a wide range of spatial and temporal datasets to support hydrological analysis globally (Mulligan, 2013b). It makes the model more suitable to use in the IGB catchment as it has vast area of ungauged and data poor mountainous environment. Historically, most of the IGB regional countries have low capacity of maintaining local hydro-climatic data. The upper catchment of the IGB region has low representation of hydro-climatic data since the most of the upland area has very few ground stations to collect hydro-climatic datasets (Higuchi et al., 1982). The reliance of WaterWorld on spatial, remotely sensed datasets, makes it valuable in such settings.

The WaterWorld model includes the 'FIESTA-delivery model[5]', which is also a hydrological model designed for the better understanding of hydrological properties of cloud forests (Mulligan and Burke, 2005). The FIESTA hydrological model is an integral part of the WaterWorld model. The model was designed to better understand the spatial and seasonal variation of above ground hydrological fluxes. Although the model was originally developed for the tropical cloud forests, it is suitable for all mountainous regions and can be used to assess land cover and climate change impact on water production and some hydrological regulatory ESs such as soil erosion and sedimentation processes. The model has been widely used in Latin America, Africa and Asia (Mulligan, 2013b). The model is a process-based spatially distributed model that models water balance on a monthly time-step but also includes a diurnal time-step to characterize the average daily dynamics within a month which is important for fog and evapotranspiration calculations. Model calculations are

[5] Fog Interception for the Enhancement of Streamflow in Tropical Areas (FIESTA) is a simulation model originally developed for the hydrological processes to understand the impacts of forest conversion in tropical montane cloud forests (TMCFs) in Costa Rica (Mulligan and Burke, 2005). The model was originally developed for the improved scientific understanding of TMCF cover in Payment for Environmental Services (PES) schemes.

carried out for one year of data using a long term (mean 50 years) climatology. The upper mountainous region of the IGB experiences some water inputs from the Cloud Water Interception (CWI) process (see, Fig 3.3-b) which has a role in annual water balance at the local level and water availability in the downstream areas. WaterWorld v2 also includes snow and ice module that is clearly important for regions like the Himalayan region. Thus, the WaterWorld has the capacity to estimate this hydrological flux; no other hydrological model has such capacity.

WaterWorld is a grid based model and can be run at a 1ha or 1km spatial resolution. There are no subsurface components since soil and base flow cannot be parameterized at these spatial scales due to a lack of data on subsurface properties. Runoff is approximated by routing the water balance down a stream flow network giving an indication of potential long term runoff with soil and groundwater stores in equilibrium. The model has now incorporated an energy budget based snow and ice model to model the contribution of snowmelt to runoff based on Walter et al., (2005). WaterWorld includes modules for distribution of rainfall through interaction with wind, precipitation through CWI inputs, solar radiation receipt, potential and actual ET on the basis of climate and vegetation cover, water balance and its cumulative downstream flow (Mulligan, 2013b). During simulation, the model iterates between four diurnal time steps (at 00:00-06:00 hrs, 06:00-12:00 hrs, 12:00-18:00 hrs and 18:00-24:00 hrs) representing the mean diurnal cycle for each of 12 monthly time steps making a total of 48 time steps for a complete simulation. Representation of the diurnal cycle is important for processes such as cloud water interception (CWI) and ET which are highly diurnal. The model incorporates modules for atmospheric processes, precipitation, ET and water balance (Mulligan and Burke, 2005).

The model has functionalities to simulate multi-scale and scenario-based analysis which are suitable for policy and decision making process (see, Bruijnzeel et al., 2011; and Saenz and Mulligan, 2013 and Pandeya and Mulligan, 2013). The model has following key strengths in terms of its use as a hydrological "policy support system". The model has ability, i) to estimate baseline hydrological fluxes on an annual and seasonal basis; ii) to assess the impacts of scenarios for land use and cover change; iii) to analyse the impacts of scenarios for climate change; and vi) to assess the impacts of multiple land and water management interventions (Mulligan, 2013b). The model has been applied at different geographical scales such as micro- to meso- scale (see, Bruijnzeel et al., 2006), country level (see, Mulligan and Burke, 2005), regional and global scale (see, (Mulligan, 2010b; Mulligan et al., 2011; Bruijnzeel et al. 2011 and Pandeya and Mulligan 2013). It also proves the strength of the chosen modelling tools to assess the intended hydrological ESs.

The model can be used to test the consequences of implementing land and water related policies. As well as an adapted version of the FIESTA hydrological model, it incorporates other models for biophysical and socioeconomic processes as well as options for designing and implementing scenarios of climate and land use changes. The model can run either 1-square km or 1-hectare resolution within 10-degree or 1-degree tiles respectively (Mulligan, 2013b). For 1-hectare simulations only the DEM and its derivatives have a resolution of 1 hectare with all other input data being sub-sampled from their native resolutions of between 250m and 1km (Mulligan, 2013b). The WaterWorld model has also a capability of uploading users' own data if they have better resolution or more recent data than in provided in the global SimTerra database. The modelling results are provided both visually and as GIS files for download and further analysis. Such analytical benefits of the model would help better understanding of hydrological ESs production of selected sites or catchments globally.

3.8.1.1 Modelling water quantity

The model estimates average diurnal and seasonal precipitation, water balance, evapotranspiration processes and fog contributions to overall precipitation (Mulligan and Burke, 2005; Bruijnzeel et al., 2011 and Mulligan, 2013b). The model estimates annual water balance by calculating total annual precipitation (i.e. wind-corrected rainfall plus fog inputs) and then deducting annual actual evapotranspiration. The model only simulates the above ground components of hydrological cycle, and does not consider soil moisture, groundwater or canopy water balance, so base flow and throughflow are not represented in the model (Mulligan, 2013b). Since soil and sub-surface datasets are not consistently available at an appropriate spatial and temporal scale, it is impossible to simulate infiltration, runoff generation and soil water storage at the IGB scale. The model also does not incorporate the climate feedback between land surface vegetation and rainfall generation (in common with most other hydrological models) since there is no clear scientific evidence to link vegetation cover to precipitation generation (Zhang et al., 2001).

The quantitative assessment of evapotranspiration in WaterWorld is a simple energy driven model which does not account for vegetation characteristics other than the Leaf Area Index (LAI), height and cover of three coexisting functional types (tree, herb and bare) (Mulligan, 2013b). The model also calculates potential evapotranspiration (PET) on the basis of energy and atmospheric demand, which is then combined with non self-shaded surface area available for the interception of radiation/evaporation of water to produce the approximate AET (see Mulligan, 2013b). The equations of hydrological calculation are listed in Appendix II.

AET has a significant influence in water balance and thus water availability at locally and in downstream areas. The combination of two separate processes (i.e. evaporation from soil surface and water bodies, and transpiration from vegetation canopies) through which water is lost to atmosphere is called evapotranspiration. Potential evapotranspiration (PET) is the achieved with no limitation of water supply, while actual evapotranspiration (AET) is the actual amount of water removed from surface evaporation and transpiration processes of vegetation canopies under the existing soil and vegetation constraints. Topography, air temperature, air humidity, solar radiation, wind speed and cloud frequency are the major factors affecting the rate of ET.

Cumulative downstream outflow is calculated as total runoff available after deducting AET from the total precipitation amount. Since the model does not account for surface and sub-surface water fluxes (such as soil moisture, groundwater and canopy water balance), the cumulative downstream outflow is not entirely equivalent to surface runoff which may also have baseflow components that are not represented in the WaterWorld (Mulligan, 2013b). Vegetation interception and evapotranspiration characteristics significantly affect the total cumulative downstream outflow.

3.8.1.2 Modelling water quality

WaterWorld also has the capability to assess some water related quality/regulatory ESs such as gross soil erosion and sedimentation (Mulligan, 2013b). The WaterWorld (v2) incorporates soil erosion, transportation and deposition modules. The erosion model is based on the Thornes equation (Thornes, 1990).

$$E = kQ^2S^{1.67}e^{-0.07V_c}$$

Where E is erosion (mm/hr), k is a soil erodibility coefficient which currently is a constant held at 0.2 throughout the model domain since there is no available information on soil erodability, Q is runoff (mm/hr) which is derived from the FIESTA model, S is the tangent of the slope gradient which is derived from the SRTM DEM and Vc the vegetation cover based on the MODIS VCF (circa 2000 – 2005) Landsat imagery (Sexton et al., 2013). Sediment transport is determined by the transport capacity Tc which is calculated according to stream power which is a function of runoff and slope (Kirkby, 1976).

$$T_c Q^{1.7} sin(S)^{0.001}(1 - V_c)$$

Sediment transport S is a function of sediment inputs from upstream plus local erosion, P where these are less than the transport capacity. Finally sediment deposition occurs where S is greater than P until S=P.

It is important to recognize that this model for wash erosion on a monthly time-step does not capture impacts of extreme rainfall events and landslides. Both types of events may deliver much sediment in the streams. However, since there is very little evidence upon which to project extreme event magnitudes and frequency, impacts of changing runoff can only be assessed based on the climate model (GCM) projections for changing rainfall. Furthermore, impacts of climate change on vegetation cover are also not taken into account which may have consequences for the impacts of land cover change on soil erosion. The details of model equations are presented in Appendix II.

3.8.2 The Co$ting Nature Policy Support System

The Co$ting Nature Policy Support System (PSS) is a data and model-based spatial tool to assess ecosystem services provided by terrestrial landscapes in order to improve the understanding for conservation prioritization and planning (Mulligan et al., 2010b and Co$tingNature V2, 2013a). The model is aimed at incorporating ecosystem service provision and benefits information into the conservation prioritization and planning (Co$tingNature V2, 2013a). It is designed to assess the ES provisions and benefits such as freshwater, carbon, biodiversity and tourism related services in terms of their potential services as well as realized at local to global scales. The model also identifies the beneficiaries of these services and assesses the impacts of human interventions upon them (Mulligan et al., 2010b). This model incorporates detailed spatial datasets at 1-square km and 1-hectare resolution for the entire world, spatial phenomenological (rule based) models for ecosystem service production consumption along with scenarios for climate and land use. The model calculates the baseline status of current ecosystem service provision and allows a series of interventions (policy options) or scenarios of land use change to be applied to understand their impact on ecosystem service delivery. All outputs are expressed in relative terms as indices from 0-1 globally. The indices represent priority across the world and so that very different services and priorities can be combined in aggregate indices to which the user can they apply specific weights (Co$tingNature V2, 2013a). Ecosystem services for the scenario are calculated using spatial surrogates.

The research uses the Co$ting Nature model to understand the broader context of ecosystem services beyond water and the potential co-benefits or trade-offs between water and other ecosystem services under baseline and scenario conditions. The model is able to assess conservation priorities based on the overlap of various conservation schemes over the landscape. The model also examines the spatial patterns of current pressure and future threat in relative to different factors such as human interventions and climatic change scenarios. The index of current pressure is the combination of human pressures such as relative crop intensity, relative grazing intensity, relative fire frequency, relative population pressure, relative dam intensity and relative infrastructural density. Similarly, the index of future threat combines land use change, climate change and infrastructural change. The threats are assumed to be related to accessibility to populations through the roads network. The threat of deforestation is assumed to scale with proximity to existing deforestation fronts according to MODIS VCF change data (www.kcl.ac.uk/geodata), threats from infrastructure are assumed to scale with projected change in GDP and threats from population to scale with projected population change (Co$tingNature V2, 2013a). Threats from climate change are assumed to scale with 17GCM ensemble projected IPCC AR4 A2a temperature and precipitation change to the 2050s (Co$tingNature V2, 2013a).

The selection of Co$ting Nature for this study is based on its relevant spatial scale for both regional and local study and its ability to examine a wide range of ecosystem services. In Co$ting Nature, potential water provisioning services for each cell are first calculated as the sum of clean water availability from upstream. Realized water services are based on the availability of freshwater in relation to downstream demands from dams, population and croplands distribution. For water quality, the model calculates the human footprint on water index in which the potential water quality in each pixel represents the cumulative impact of point (mining, oil and gas, roads and urban areas) and non-point (pastures and croplands outside the protected areas) sources of contamination. Each of these is given an equal weighting in terms of its capacity to generate contamination and for each pixel the human footprint index represents the percentage of water coming from upstream that is influenced by these point and non-point source of contaminants. This is calculated as rainfall falling on these ‘polluting’ land areas cumulated downstream with rainfall falling on non-polluted areas. Areas with extensive agriculture or expansive urban areas will have a significant impact on freshwater availability in the downstream areas. The details of model documentation are presented in Appendix III.

3.8.3 Limitations of using hydrological modelling tools

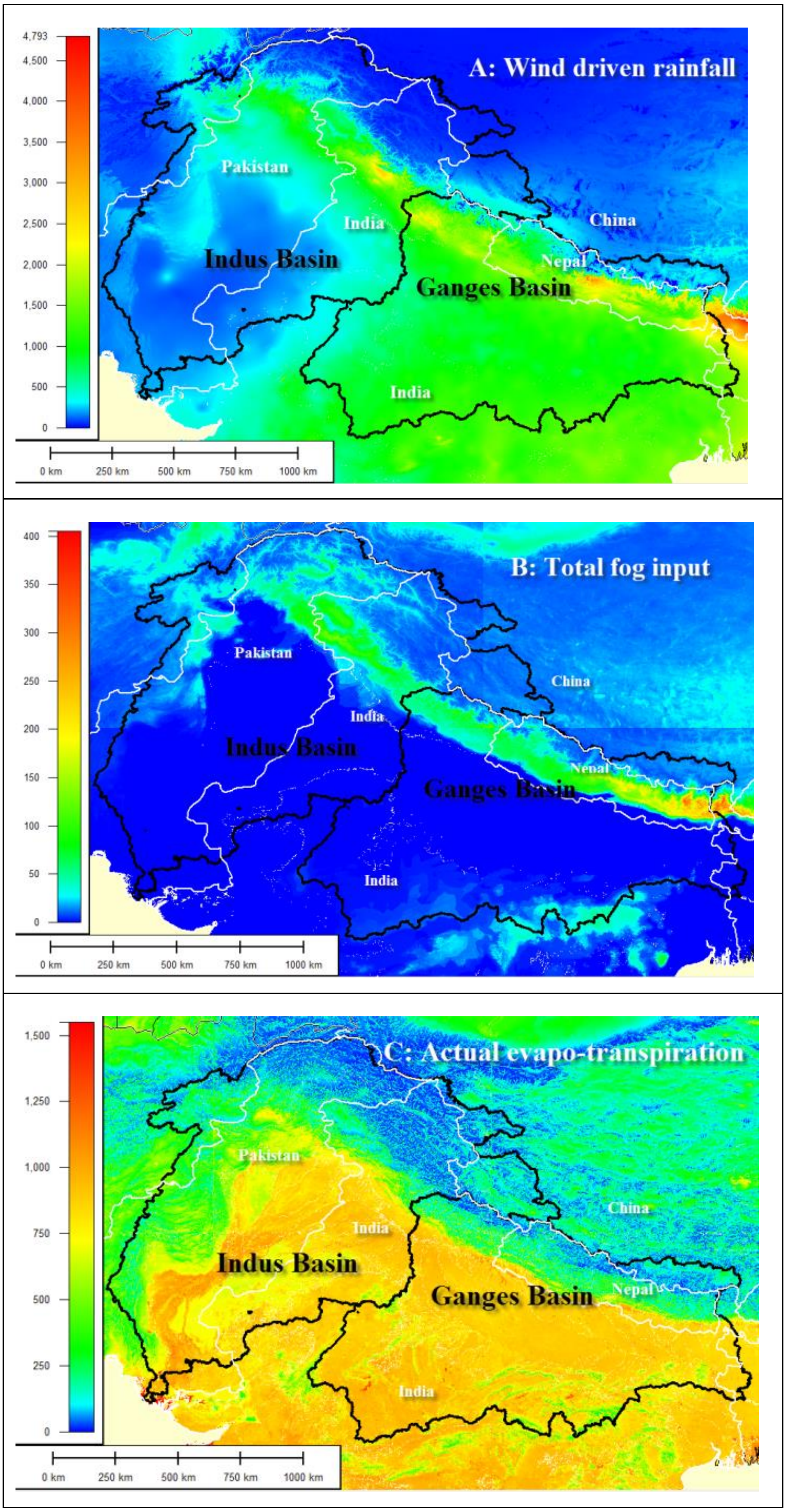
Here we also present some of the limitations of the modelling approach applied for both mountain catchments. The modelling framework had to rely on some global datasets such as wind speed (that has a role in quantifying wind-driven rainfall and fog inputs) and the MODIS cloud frequency, these have a low spatial resolution and may not be representative of variability in this small catchment. The land cover related impacts on hydrology in WaterWorld may not capture some of the variability in hydrological behaviour between forest types which may have a significant impact on ET processes. The model is a water balance model and thus does not account for subsurface hydrology. Thus, the model cannot capture flow regulation effects of land use on infiltration dynamics since it does not have a subsurface component. The modelling results do however help to i) understand the change in water availability at the catchment scale as a result of changes in land cover and land use, and ii) understand how these changes scale with the distribution and the scale of land use change as is necessary for influencing decision making processes.

Although the WaterWorld and the Co$ting Nature PSS are the best suited models for the hydrological ESs assessment at the IGB as well as local scale catchments, both models are hugely reliant on globally scale data for a number of hydrological and bio-physical datasets. Originally, the modelling tools are designed to assess the hydrological ESs of the data poor regions of the world. The use of WaterWorld model for the crop ET assessment of the IGB catchment represents the best results as the catchments are less representative for a number of hydro-climatic datasets.

However, the regional and global datasets may not appropriately represent the local conditions. The research has collected local datasets such as rainfall and wetland to improve the model database for local scale assessment. The model still has to rely on various global datasets while estimating hydrological ESs of selected mountain catchments. In addition, the WaterWorld model is not capable to assess some regulatory services such as the characteristics of peak flows or low flows. Thus, the use of these models for the local catchment scale hydrological modelling must be understood with caution.

3.9 Preliminary hydrological ESs assessment

The IGB catchment has a significant hydro-climatic variability both temporally and spatially (see, Fig. 3.3, below). It has a huge influence on the distribution and availability of hydrological ES. The annual total rainfall varies across the region with an average of 1100 mm/yr in the Ganges basin (Mulligan et al., 2011). It varies seasonally from less than 100 mm per year in the arid Indus basin to more than 4000 mm per year in the north-eastern Ganges. Seasonally, more than 80% rainfall occurs during the monsoon period between June and September. High mountains form a barrier to the Indian monsoon coming from the Bay of Bengal and the Indian Ocean, and that results in higher rainfall along the Himalayan foothills. Much of the Ganges basin and the northern part (upstream) of Indus basin receive higher rainfall compared to the rest the IGB. The eastern parts of the basin (i.e. the Ganges basin) receive much higher annual rainfall compared to the Indus basin in the west (Fig.3.3, below). Some of the driest parts of the lower Indus basin receive no rainfall at all. Snow and ice melting is also a major source of freshwater inputs especially during the dry period of the year. Foggy and cloudy climates are existed along the high mountainous region of the Himalayas where a small amount of water input also supplements from fog deposition and its impaction.



A: Wind driven rainfall
4,793
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Pakistan
India
China
Nepal
Indus Basin
Ganges Basin
India
0 km
250 km
500 km
750 km
1000 km
B: Total fog input
400
350
300
250
200
150
100
50
0
Pakistan
India
China
Nepal
Indus Basin
Ganges Basin
India
0 km
250 km
500 km
750 km
1000 km
C: Actual evapo-transpiration
1,500
1,250
1,000
750
500
250
0
Pakistan
India
China
Nepal
Indus Basin
Ganges Basin
India
0 km
250 km
500 km
750 km
1000 km

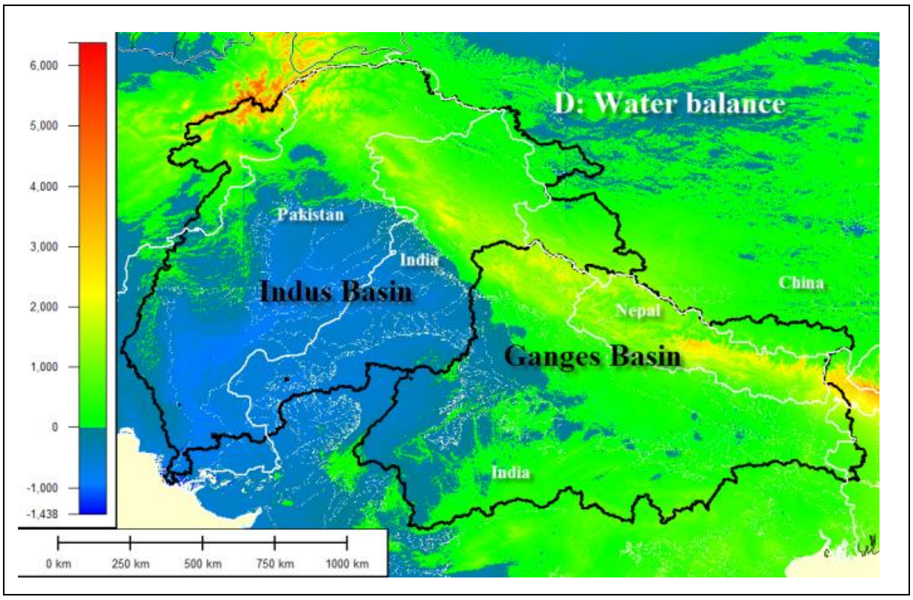


Figure 3-3: Total annual water budget (mm/yr) across the IGB catchment (WaterWorld-V2, 2013)

Fig 3.3 also shows the spatial distribution of annual AET and water balance. The WaterWorld model is based on the energy driven hydrological model which calculates AET and water balanced from the available water (in the form of annual precipitation), solar radiation, Leaf Area Index (LAI), cloud frequency. There is higher level of AET across the lowland basin where the vegetation cover is also high such as along the Indus basin corridor and much of the Ganges basin plains. It is also confirmed that the crop dominated areas are also with higher level of AET (Fig 3.3c). Finally, the model also calculated the annual water balance which is calculated by adding water inputs and deducting the total AET of the area. In the IGB catchment, there is positive water balance in most parts of the Ganges basin and northern parts of the Indus basin. As the Himalayan foothills receive very high amount of annual rainfall plus water inputs due to the high mountain cloud water interception.

Using the Co$ting Nature model, the research has also assessed the level of relative current pressure and future threats on hydrological ES. Both indicators are measured on the basis of global index. Despite the huge potential of a wide range of ecosystem services available from the basin, there is a huge scale of human pressure on existing hydrological ES. Fig 3.4 shows that the densely populated areas and higher percentage of cropland coverage have greater impact on hydrological ES. Relative pressure index is derived by a combination of various pressure factors currently existing in the region. These include the combination of relative population, relative fire frequency, relative grazing intensity, relative agricultural intensity, relative dam density and relative infrastructural density. Relative fire frequency is based on an analysis of the mean burn frequency from 2001-2010 from the MODIS burnt area product (Mulligan 2010a). Grazing intensity is calculated according to head of cattle for managed grazing and wild land grazing after (Wint and Robionson 2007). Agricultural intensity combines the fractions of cropland and pasture in each pixel. Pressure from dams is calculated as the cumulative upstream number of dams using the Global Dams Database (Mulligan et al. 2009). Infrastructural pressure is calculated from the location of dams, mines, oil and gas, roads and urban infrastructure (Co$tingNature-V2, 2013a).

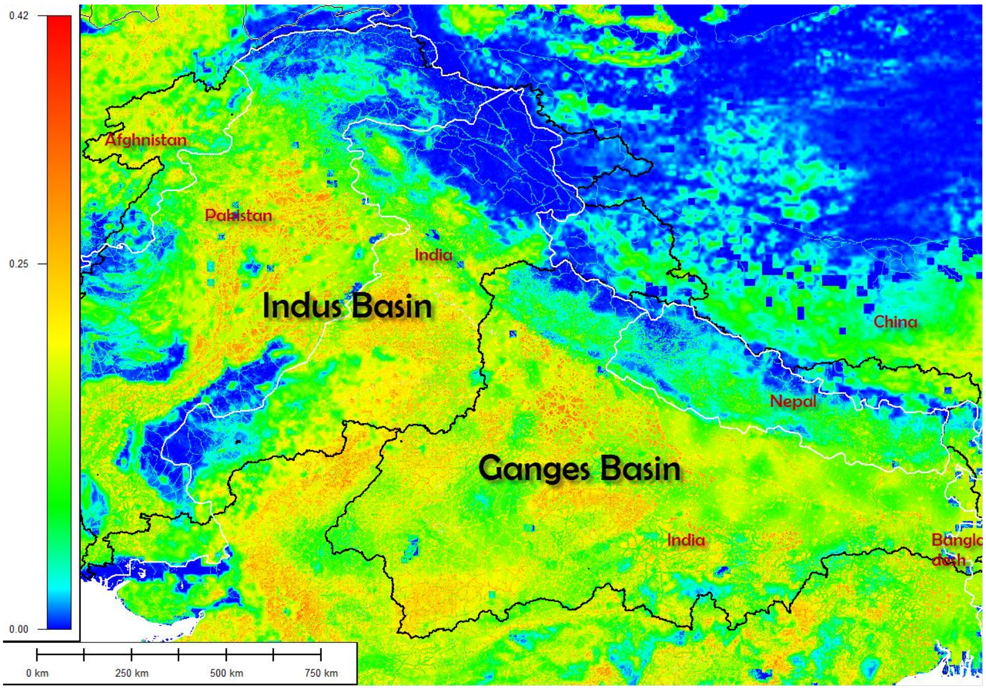


Figure 3-4: Relative pressure index class (0-1) (Costingnature-V2, 2013b)

There is a higher degree of relative pressure in lowland areas of the IGB catchment (Fig. 3.4, above). Due to higher population density, agricultural intensity and infrastructural expansion, the plain areas have higher level of human pressure on various ecosystem services including hydrological ES.

Relative threat index (Fig. 3.5, below) is being calculated based on the future threats according to accessibility, proximity to recent deforestation (MODIS), projected change in population and GDP, projected climate change, current distribution of night time lights (Co$tingNature-V2, 2013b). Threats are distinct from pressures because pressure refers to current pressure whereas threat is the potential to increase pressure into the future. The Co$tingNature relative threat index combines threats of land use change, climate change and infrastructural change (Co$tingNature-V2, 2013a). All threats are assumed to be related to accessibility to populations through the roads network. The threat of deforestation is assumed to scale with proximity to existing deforestation fronts according to MODIS VCF change, threats from infrastructure are assumed to scale with projected change in GDP and threats from population to scale with projected population change. Threats from climate change are assumed to scale with 17GCM ensemble projected IPCC AR4 A2a temperature and precipitation change to the 2050s. Finally remote threats such as mining and oil and gas (that may be distant from populations, urban areas and roads) are assumed to be greater in proximity to existing night time lights. All of these threats are given equal weight and scaled from 0-1 in the final threats map (Co$tingNature-V2, 2013b).

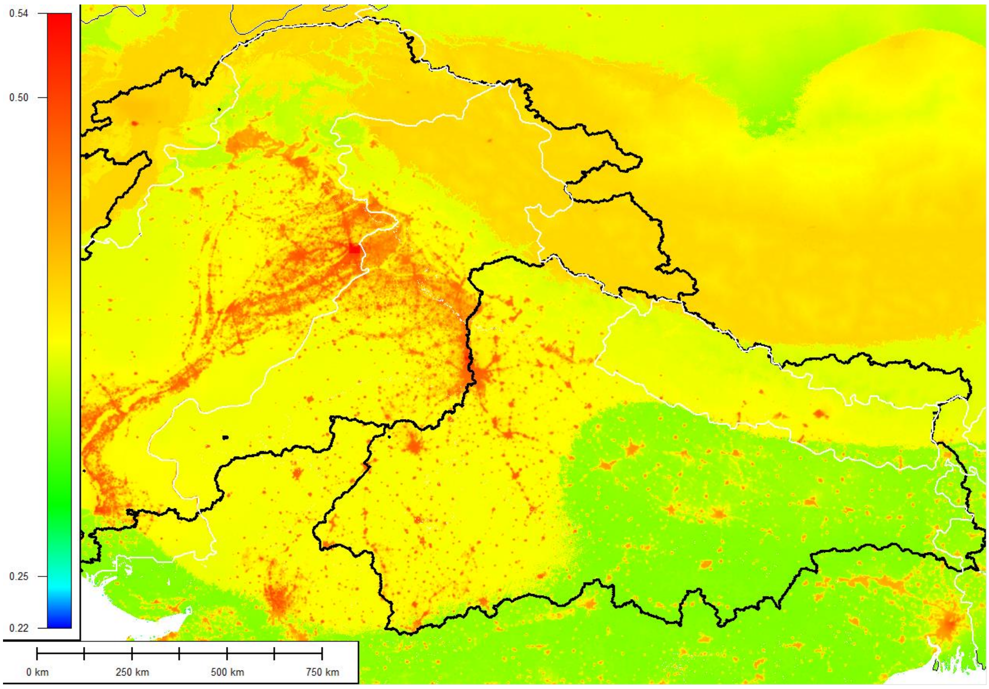


Figure 3-5: Relative threat index class (0-1) (Costingnature-V2, 2013b)

The Fig 3.5 shows the greater threat is confined in the human dominated areas especially in the north-western parts of the IGB basin where land use and infrastructural change is very high. Some of the semi-arid southern Indus basin and western part of the Ganges basin are vulnerable to climate change related threat which also makes the region more threatened in the future. Since the model gives equal weight to all three main variables, the result maps shows the higher degree of threats in the western and southern parts of the basin as well as densely populated areas across the lowland areas.

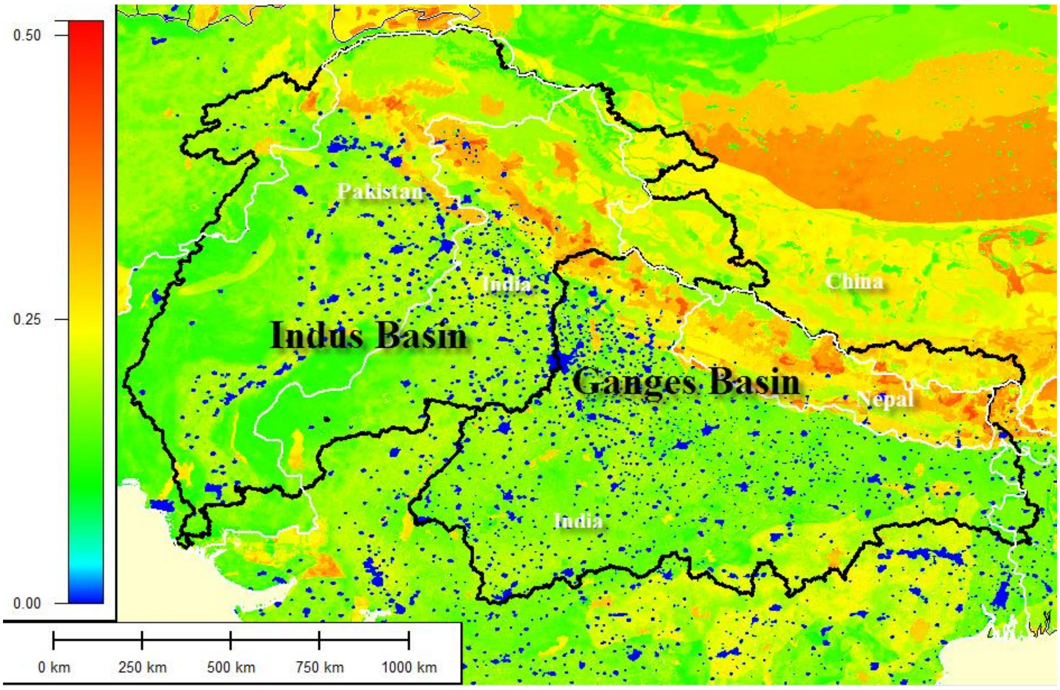


Figure 3-6: Relative total nature conservation priority index (class 0-1) (Co$tingNature-V2, 2013b)

Figure 3.6 shows the IGB region with relative global conservation priority index. Relative nature conservation priority index combines total potential services (for all services i.e. water, carbon storage and sequestration, hazard mitigation and nature based tourism) and total nature conservation priority (which combines the relative conservation priority index, biodiversity with current pressure and future threats). Relative aggregate nature conservation priority index (potential services) is thus a measure of potential value for services coupled with conservation priority according to perceived value and risk of loss (CostingNature-V2, 2013a). The figure shows very little or no conservation priority in human dominated landscape such as urban areas and agricultural land. It also reflects the higher conservation priority in protected areas where various other conservation schemes are also overlapping with the national park programme. Geographically, upper catchment has better conservation priority indices compared to downstream basin areas. Upper basin including the Himalayas is rich not only for hydrological ESs but also its rich biodiversity and eco-tourism ESs.

3.10 Overall summary

This research applies spatial based hydrological modelling tools (the WaterWorld PSS and the Co$tingNature PSS), appropriate statistical methods and ground based data collection, questionnaire survey and stakeholder interaction in order to assess the hydrological ESs of IGB and selected mountain catchments in the middle mountainous region of the Himalayas. We explained the need of spatially explicit quantitative assessment as well as scenario modelling for better understanding of future change of hydrological ESs in the basin. Then, the chapter discussed the delineation process of selected sites and their major characteristics. It followed with the data acquisition and development processes. The selected modelling tools are being provided with the SimTerra database, a database of globally available best datasets (at 1km and 1ha resolution) on hydro-climatic, biophysical and socio-economic parameters. Then, we described the ground data collection process for the improvement of some modelling datasets. Fieldwork activities included a questionnaire survey for the qualitative assessment of local perception on hydrological ESs. It follows with the description of methodological approaches for three main objectives representing chapter 4, 5 and 6. Then, next section describes model specification of WaterWorld and Co$ting Nature, their characteristics and strengths for the hydrological assessment in the IGB catchment. The chapter also briefly explained the data constraints and key limitations while using WaterWorld and Co$ting Nature model.

The research has some methodological innovation such as the modelling of crop ET at administrative region scale which is essential for water resources management in the basin. Similarly, we are assessing fog water inputs and it is especially important for the selected mountain catchments where such hydrological effect may have significant effect on water availability. Estimating gross and net soil erosion in the mountain catchments would help to inform policy levels on how watershed conservation based LUCC scenarios would alter the sedimentation level in streams and downstream reservoirs. Thus, the selection of methodological approach has a combination of advanced hydrological modelling tools (including innovative approaches) and socio-ecological methods that would be replicable to other regions.

Finally, this section also presented some preliminary results of hydrological ESs using WaterWorld PSS and Costing Nature PSS for the IGB catchments. The preliminary results showed the spatial distribution of four major hydrological fluxes in the basin. The current pressure, future threats and the relative conservation priority index have been also presented to understand the impact of human intervention across the IGB catchments.

Chapter 4 Modelling crop evapotranspiration and potential impacts on future water availability in the Indo-Gangetic Basin

Context for this publication

This chapter is in published paper format and addresses a key research objective set in the chapter 1 section 1.4 (i.e. the modelling crop ET scenarios and its potential impact on future water availability at the IGB administrative region scale). The findings are published in a peer reviewed paper (see, Pandeya and Mulligan, 2013). Croplands are extensive in the IGB plains and consume more water than any other sector. Moreover, the water resources are highly contested among different water use sectors and the allocation of available water is subjected to fraught relations between administrative regions and countries. Thus, the understanding of water consumption level in croplands and its potential impact on water availability is of paramount importance in water resources policies for the IGB and that is the central theme of this publication.

The overall research focuses on major hydrological ESs of regional and local importance. At the regional scale, the research has assessed crop ET related hydrological ESs whereas at local scale, water supply to cities and HEP production services are chosen for selected local catchments. This publication (i.e. chapter four) presents an important role of crops carrying hydrological ESs of the IGB regions. It also discusses the future implications of cropland growth scenario. It follows by local scale hydrological ESs assessment of selected mountainous catchments. While chapter five is assessing water supply provisions to downstream urban areas by a Protected Area catchment, the chapter six is examining water supply to HEP production in a human dominated catchment.

Since the use for water is set to grow to fulfil the demand from the existing and increased croplands, the findings are stressing for a better integration of cropland water consumption in hydrological ESs based research. Although the recently evolved 'Virtual Water' concept could be an alternative policy instrument to deal with the region's highly valuable hydrological resources, more rigorous analysis would be needed on how this concept can support hydrological policies of the region.

4.1 Introduction

4.1.1 Cropland and its freshwater use – a global perspective

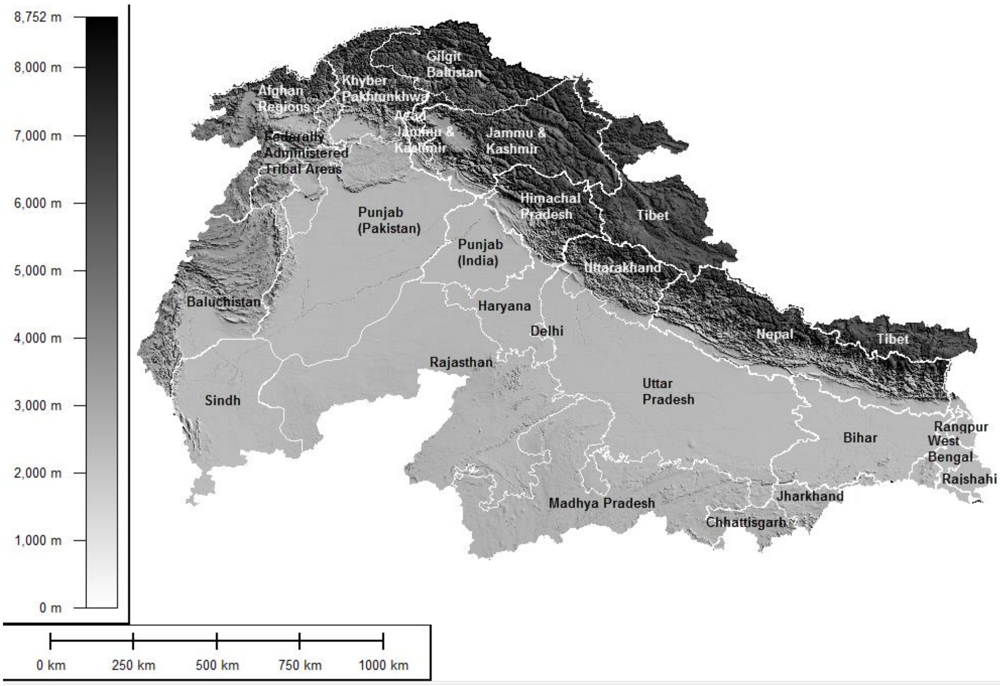


Figure 4-1: An overview of Digital Elevation Model (DEM) map of the IGB basin (masl) [Source: (Farr and Kobrick 2001)]

4.1.2 The Indo-Gangetic Basin

4.1.2.1 Basin and its freshwater resources

4.1.2.2 Water and food security now and in the future

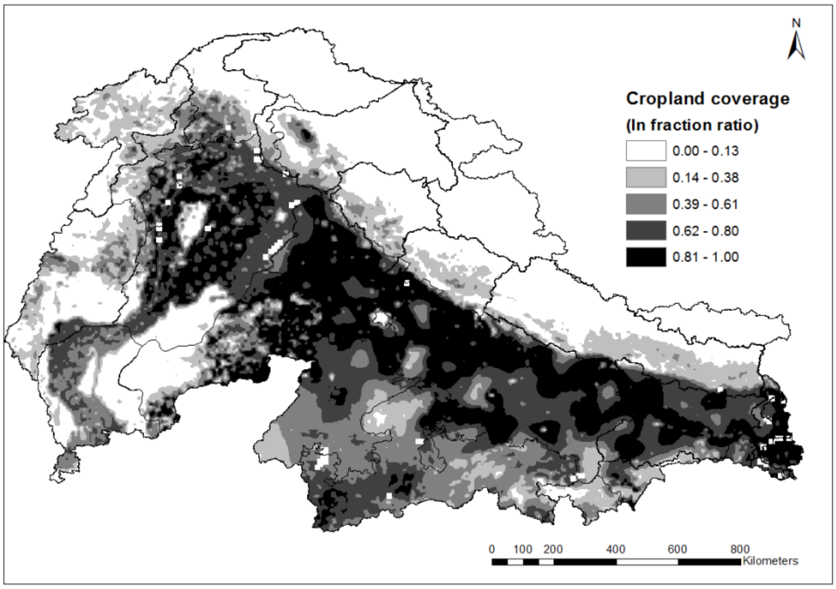


Figure 4-2: Fractional ratio of cropland coverage in baseline year 2000 [source: (Ramankutty et al. 2008)]

4.1.2.3 Cropland distribution and freshwater use

4.1.2.4 Aim and objectives of the study

Table 4-1: Current freshwater use by agricultural lands in the IGB region

River Basin	Rain-fed agricultural land cover (%)	Precipitation use in rain-fed agriculture (%)	Irrigated agricultural land cover (%)	Precipitation use in irrigated agriculture (%)	Net runoff of total precipitation (%)
Ganges	52	32	25	18	37
Indus	14	15	20	31	10

Adapted from (Eastham et al. 2010a, Eastham et al. 2010b)

4.1.3 Hydrological services supporting crops

4.2 Materials and methods

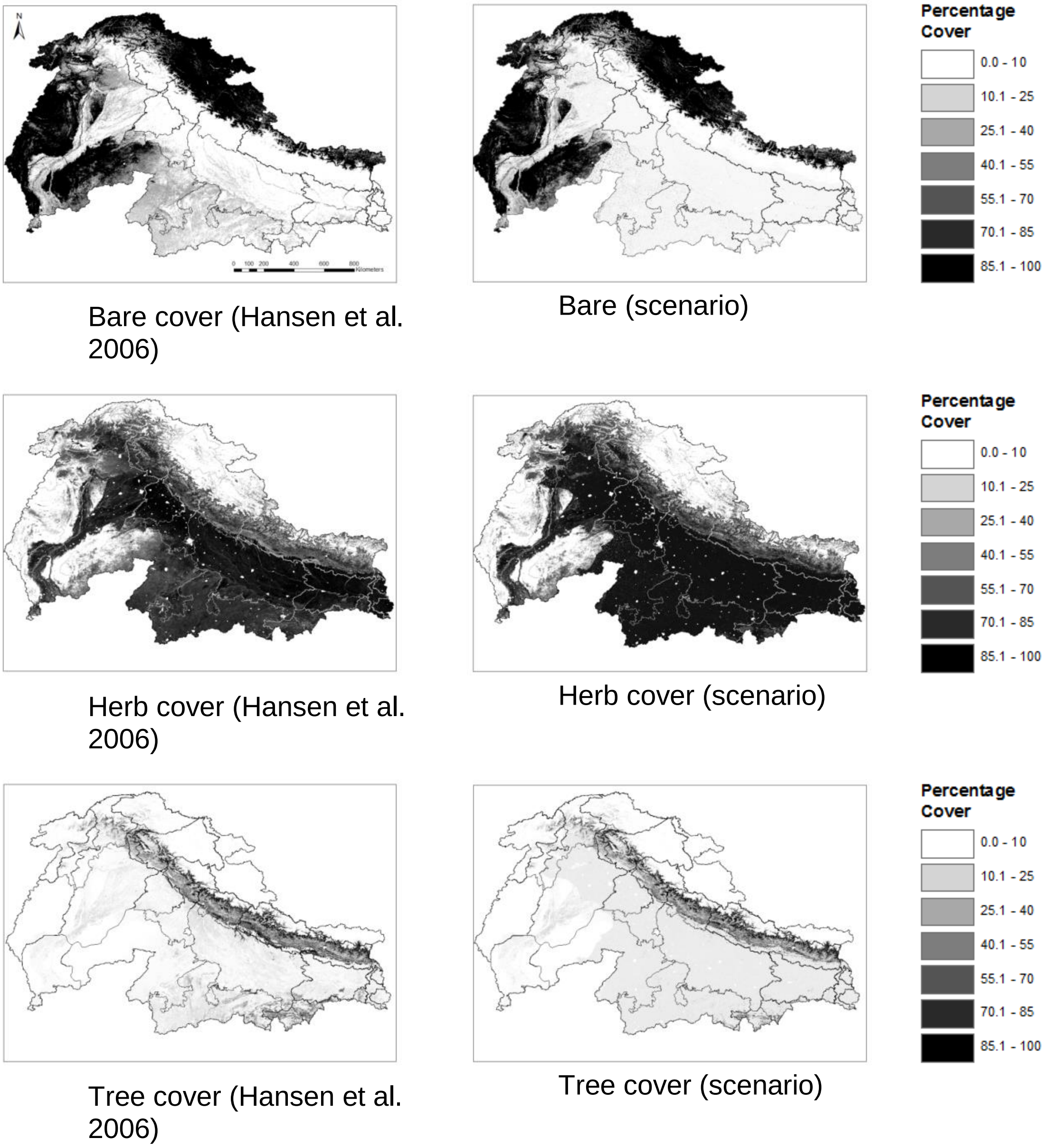


Figure 4-3: Percentage coverage of land use types (baseline vs scenario)

4.3 Results and discussion

4.3.1 Cropland growth scenario for 2050

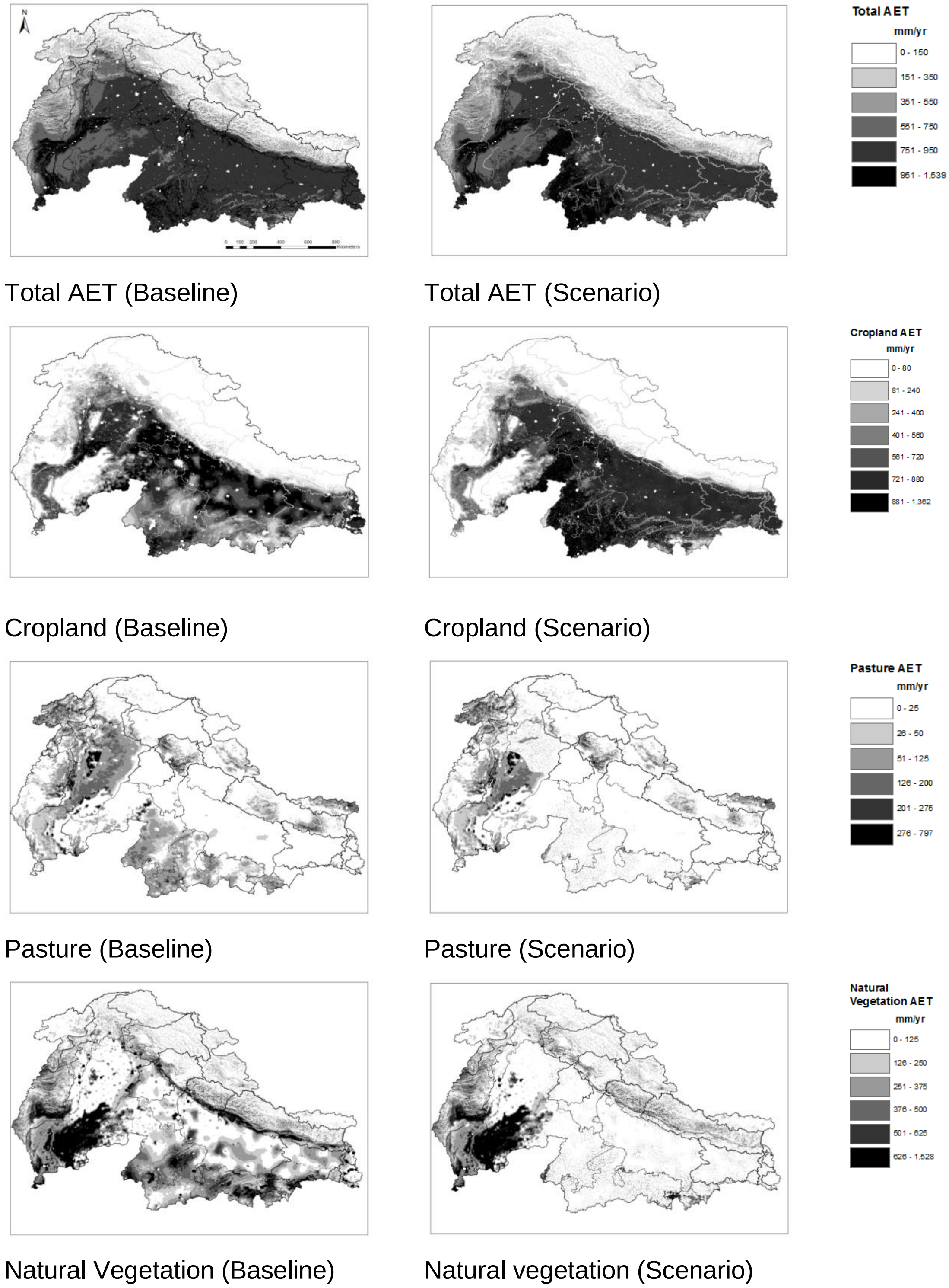


Figure 4-4: Baseline and scenario AETs (mm/yr) of land use types

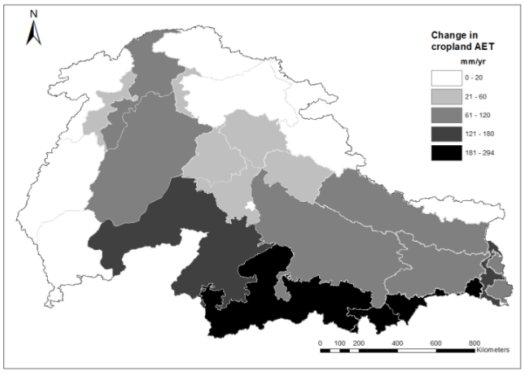


Figure 4-5: Change in crop AET between 'More Cropland' scenario and baseline (mm/yr)

4.3.2 Change in crop AET and its implications on water availability

Table 4-2: Baseline average AET (mm/yr) at regional/country scale

Region	Cropland	Natural Vegetation	Pasture	Total AET
Afghan Regions	32	100	93	226
Azad Jammu & Kashmir	107	217	15	341
Baluchistan	91	322	36	450
Bihar	646	210	1	857
Chhattishgarh	205	460	66	732
Delhi	125	725	6	858
Federally Administered Tribal (FAT) Areas	114	186	51	351
Gilgit-Baltistan	1	66	4	72
Haryana	753	126	3	883
Himachal Pradesh	52	142	58	253
Jammu & Kashmir	30	119	4	154
Jharkhand	383	359	9	752
Khyber Pakhtunkhwa	152	131	32	316
Madhya Pradesh	474	343	50	868
Nepal	82	244	26	353
Punjab (India)	723	151	1	876
Punjab (Pakistan)	470	197	103	772
Rajasthan	466	313	39	819
Rangpur-Rajshahi	658	185	9	853
Sindh	306	477	49	833
Tibet	0	93	28	122
Uttar Pradesh	689	183	8	881
Uttarakhand	96	275	1	374
West Bengal	549	288	0	838

Source: (WaterWorld-V2 2012b)

Table 4-3: Change in AETs (mm/yr) between 'More Cropland' scenario and baseline land cover

Regions	Cropland	Natural Vegetation	Pasture	Total AET
Afghan Regions	2	-1	-1	0
Azad Jammu & Kashmir	37	-31	-4	0
Baluchistan	1	0	0	-1
Bihar	117	-112	-1	0
Chhattisgarh	226	-97	-32	-2
Federally Administered Tribal (FAT) Areas	22	-6	-3	25
Gilgit Baltistan	0	0	0	2
Haryana	52	-31	-2	12
Himachal Pradesh	30	-29	-3	-8
Jammu & Kashmir	11	-240	-7	-8
Jharkhand	232	-10	-1	1
Khyber Pakhtunkhwa	61	-22	-15	-5
Madhya Pradesh	294	-225	-45	-15
Nepal	81	-81	-8	21
Punjab (India)	58	-57	0	48
Punjab (Pakistan)	78	-18	-38	1
Rajasthan	156	-79	-28	0
Rangpur-Rajshahi	102	-90	-9	4
Sindh	2	-1	0	4
Tibet	0	0	0	23
Uttarakhand	56	-63	-1	2
Uttar Pradesh	100	-84	-7	7
West Bengal	180	-179	0	19

Source: (WaterWorld-V2 2012b)

4.4 Conclusions and policy implications

Chapter 5 Understanding hydrological ecosystem services of a protected area catchment in the middle hills region of the Himalayas

5.1 Background

As the overall aim of the research is to better understand major hydrological ESs of IGB catchment both at regional and local scales, we have assessed cropland ET of the IGB catchments in the previous chapter. From the IGB scale assessment, the research now focuses on local scale hydrological ESs assessment in the middle mountainous region of the Himalayas. The rationale of the selection of both mountain catchments is explained in section 1.3 above. The selected two mountain watersheds represent a Protected Area (PA) watershed and a human dominated watershed environment. This chapter deals with water provisioning services of the PA watershed and how conservation led land cover change would affect quantity and quality (sedimentation load) of the water resources.

The middle mountainous region of the Himalayas is one of the rich zones for various ecosystem services including freshwater (Murray et al., 2009), biodiversity conservation (Conservation International, 2012), and eco-tourism (Nepal, 2000 and Nepal and Chipeniuk, 2005).The entire Himalayan region including the middle hills areas have been recognized for different conservation priorities (Fig 5.1, below). Major international recognitions include Protected Area (PA), Important Bird Areas (IBA), Global200 Eco-regions, Hotspots, Last of the Wild and Key Biodiversity Areas. It shows the importance of middle hills region for conservation of different ESs. The available ESs are under pressure due to higher population density across the region (ICIMOD, 2013).

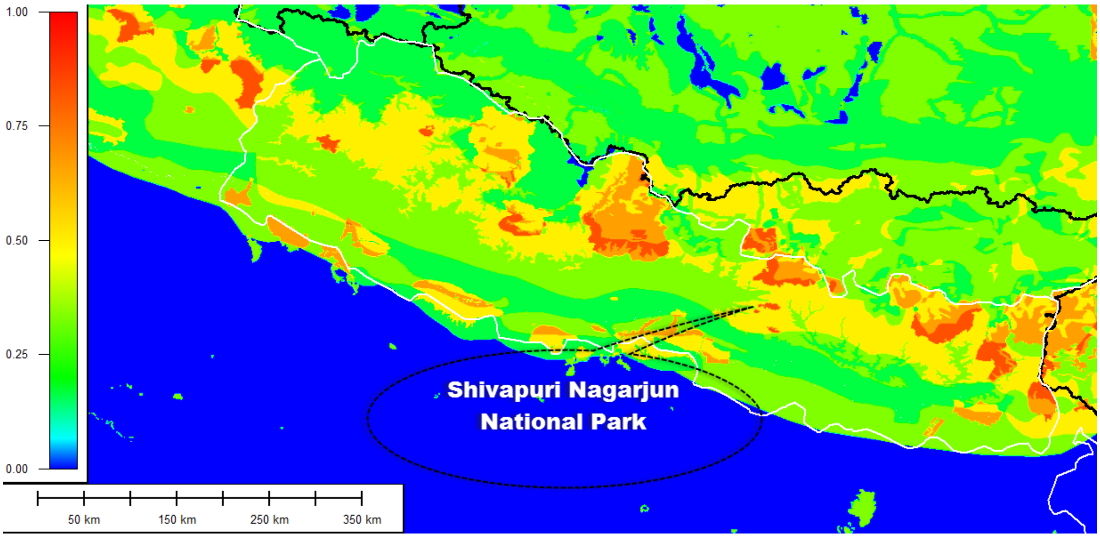


Figure 5-1: Relative conservation priority index (classes: 0-1) (Co$tingNature-V2, 2013b) [Overlap of conservation programmes - IBAs (Birdlife), Global200 Eco-regions (WWF), Hotspots (CI), Last of the Wild (WCS, CIESIN), Important Bird Areas (Birdlife) an

To understand the freshwater ecosystem services provided by a protected area catchment, the study has selected Shivapuri Nagarjun National Park (SNNP) which is located in the middle mountainous region of the Himalayas. The SNNP catchments are the major source of clean drinking water supply (~46% of total water supply) for Kathmandu valley located in the downstream of the park catchments. Since Kathmandu valley is home for more than 4 million inhabitants, the PA catchments have a crucial role in maintaining freshwater ESs to the downstream users.

After the realization of catchment's rich ecosystem services primarily freshwater, biodiversity, wildlife habitat and cultural/eco-tourism benefits, the central government and the Department of National Park and Wildlife Conservation (DNPWC) (with the support of external donors) started watershed conservation programmes from the early 1970s. Since then, the PA catchments have experienced various conservation interventions over the last four decades (NTNC, 2004). With the successful implementation of various conservation interventions, the park's ability to provide hydrological ESs may have been improved. The annual water availability may have also increased along with the improved quality services. The influence of Park and its conservation achievements on hydrological ESs is crucial for the freshwater supply to the downstream areas. Since the park also hosts two human settlements in the upland area, the assessment of their potential role with an integrated watershed management could be also important within the context of emerging PES programmes.

5.2 Aim of this chapter

The main aim of this study is to explore a major hydrological ESs provided by a catchment containing a protected area in the middle mountainous region of the Himalayas. First, we estimated the baseline (current) hydrological ESs (both quantitative and qualitative services) of the SNNP catchments. Modelling results show the level of different hydrological fluxes and their distribution across the PA catchments. Second, we assessed the use of freshwater resources particularly in drinking water supply to the downstream urban areas. Since the catchments supply almost half of the water supply in Kathmandu valley, it is important to understand the past and present trend of water production, demand and supply. This assessment would provide the important role of the SNNP catchment in maintaining freshwater supply to Kathmandu. In the third, the study has modelled the details of hydrological ESs of a sub-catchment (i.e. Sundarijal area) for the better understanding of hydrological ESs under different plausible LUCC scenarios. Then, we also analysed people's perception on the need for PA conservation for various ESs including hydrological ESs provisions. Finally, the study has assessed the potential role of newly emerged PES programme in better management of those hydrological ESs and for conservation sustainability.

5.3 Shivapuri Nagarjun National Park Catchment – An Introduction

The Shivapuri-Nagarjun National Park (SNNP) catchment is situated in the middle mountainous region of the Himalayas [between Latitude ($27^0$44'N to $27^0$51'N) and Longitude ($85^0$14'E to $85^0$30'E)] (Fig. 5.2, below). The total area of the SNNP catchments is about 159 km^2 (including 15 km^2 area of Nagarjun area) and the altitudinal zones range between 1,320 masl to 2,732 masl with a mean elevation is about 2,000 masl.

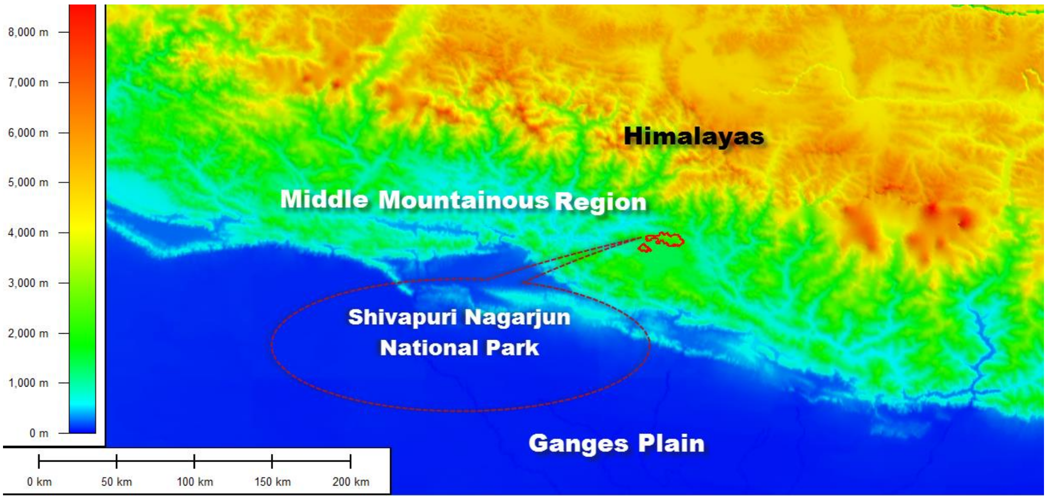


Figure 5-2: Geographical locale of the Shivapuri Nagarjun National Park catchment in the middle mountainous region of the Himalayas (Lehner et al., 2008)

The SNNP is located about 12 km north of Kathmandu which is a major urban centre in the middle hills region of the Himalayan region (Fig. 5.3, below). The SNNP catchments are some of the major freshwater supply sources to the capital. It also offers various other ESs including biodiversity conservation, eco-tourism and forest carbon sequestration. Due to its rich biodiversity and beautiful landscapes, the park is now a major tourism destination (DNPWC, 2012) and a good source of tourism revenue (NTNC, 2004). Besides the people living in the vicinity, urban dwellers in the downstream areas are hugely dependant on a wide range of ecosystem services produced by the catchment.

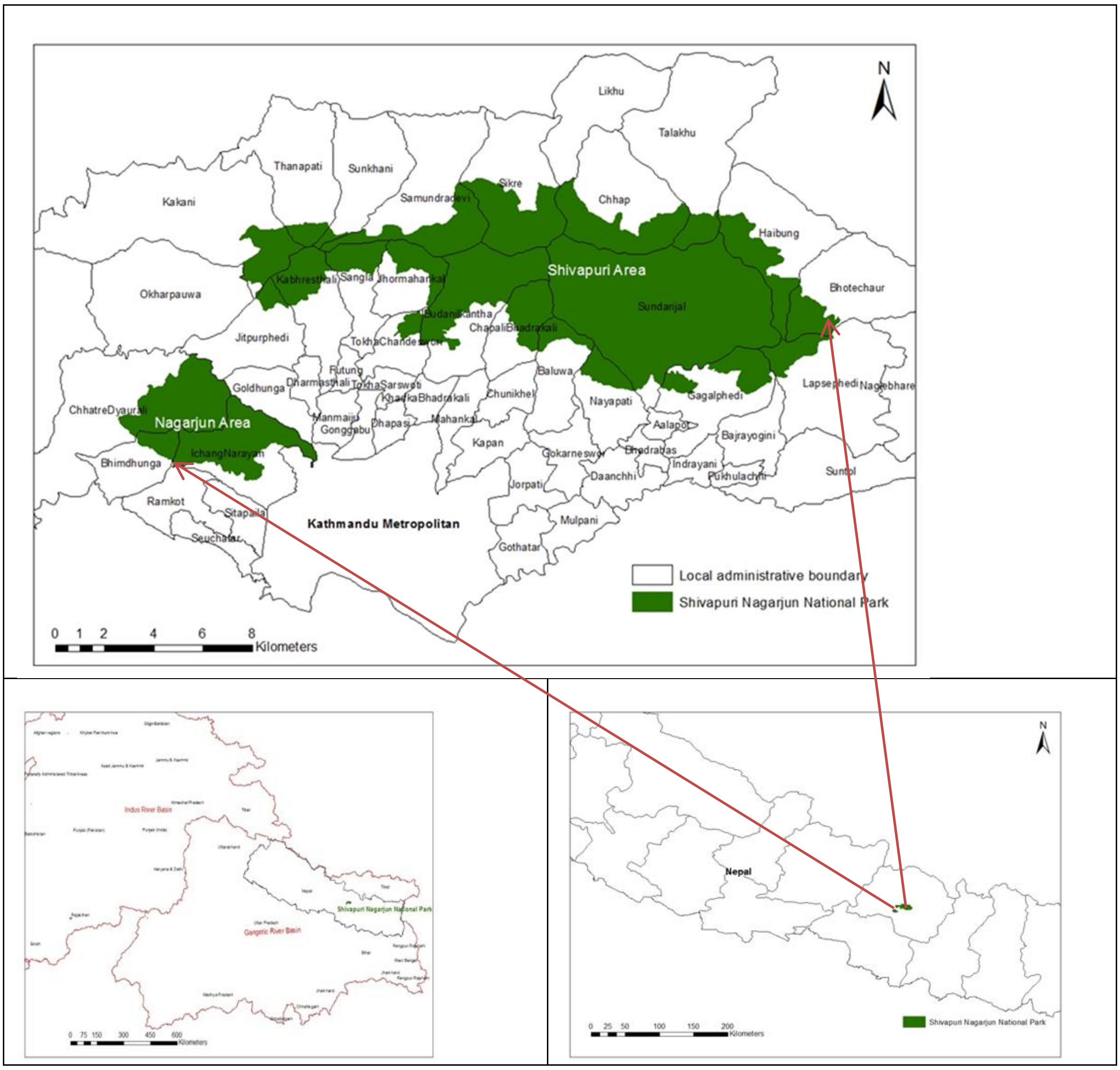


Figure 5-3: Location of Shivapuri Nagarjun National Park and adjoining local administrative areas

The Shivapuri catchment is the origin of the Bagmati River, a major river system in the middle mountainous region of the Himalayas. The river is the source of clean drinking water for the majority of the Kathmandu valley and further downstream areas where millions of people rely on the hydrological ecosystem services provided by this river system. The catchment possesses a huge hydrological significance to the downstream areas. The main use of the catchment water resources is drinking water supply to downstream urban areas. A small HEP is also situated at the outlet of one of the sub-catchments (i.e. Sundarijal) which has a 0.54 MW production capacity. The available water resources are also used in irrigation around and the immediate downstream areas.

5.3.1 Conservation interventions and land use change

Following the decades of heavy deforestation, various government departments with the help of international agencies have practiced conservation programmes primarily reforestation/afforestation activities in the catchment (NTNC, 2004). To safeguard key watershed ESs such as freshwater supply, biodiversity conservation and habitat protection, conservation programmes were first started in early 1970s with the declaration of Protected Area under the National Parks and Wildlife Conservation Act. Since then, the catchments have witnessed various conservation programmes and finally in 2009 both catchments have been formally designated as Shivapuri Nagarjun National Park (Table 5.1, below). Now, the SNNP catchments are strictly protected by the DNPWC under the rules/regulations of National Park and Wildlife Conservation.

Table 5-1: A timeline of major conservation programmes in the SNNP catchment

Year	Conservation programmes
1973	Declared Protected Area under the National Parks and Wildlife Conservation Act
1976	Establishment of the Shivapuri Watershed Reserve Project by the designation of Shivapuri Watershed Reserve and Shivapuri Watershed Development Board under the Development Board Act 1956
1983	Shivapri area demarcated in May by Gazette notification under the Shivapuri Wildlife Conservation Act and declared as Wildlife Reserve in June under the NPWC Act 1973
1984	Changed to Shivapuri Watershed and Wildlife Reserve Development Board was established under the Development Board Act 1956 to replace the 1976 designation
1985	Implemented Shivapuri Watershed Management and Fuel wood Plantation Project (1985-92) – with the support of FAO (phase I)
1992	Implemented Shivapuri Integrated Watershed Development Project (1992-97) – with the support of FAO (phase II)
2002	Changed to protected area status from Watershed and Wildlife Reserve status to Shivapuri National Park
2003	Brought a policy to give some protected areas including Shivapuri National Park to NGOs for management
2004	Preparation of Draft Management Plan for the Shivapuri National Park
2009	Establishment of Shivapuri-Nagarjun National Park

Source: (NTNC, 2004; NTNC, 2009 and DNPWC, 2012)

The land use change in the park has been hugely influenced by a series of conservation interventions (NTNC, 2004). Major watershed management programmes were afforestation/reforestation and soil stabilization activities, which have improved the forest coverage across the catchment. Upland communities located within and surrounding areas are voluntarily supporting the conservation programmes implemented by PA authority.

5.3.2 Park and human interaction

Most of the conservation interventions implemented in developing countries are directly affecting rural poor and disadvantage people (Adams and Hutton, 2007) as the rural people heavily rely on available natural resources for their livelihoods. Due to conservation rules of protected areas, communities were either displaced from their ancestral land or seriously affected due to restrictions in resource use (Adams and Hutton, 2007). Vulnerable and marginalized people living within and surrounding PAs bear the consequences of conservation activities as deterioration in their livelihood opportunities. Due to strict rules of National Park Programme, local communities do not have access to essential natural resources such as fuelwood, fodder and various non-timber forest products.

The DNPWC has designated surrounding and immediate downstream areas as buffer zone (Fig 5.4, below) in order to maintain the conservation status of immediate surrounding areas. Buffer zone area covers 23 village development committees (VDCs) and located in and around the park with a total household no. about 25,300 and total population about 114,500 (CBS, 2012). The concept of buffer zone is aimed to support affected communities with various conservation and development programmes. Such programmes may support to achieve the overall aim of park conservation. There are also about 380 households and 1900 people (CBS, 2012) currently residing within the park (Mulkharkha and Okhareni village) and they heavily depend on park resources to fulfil their basic needs such as fuel wood, fodder, herb and timber.

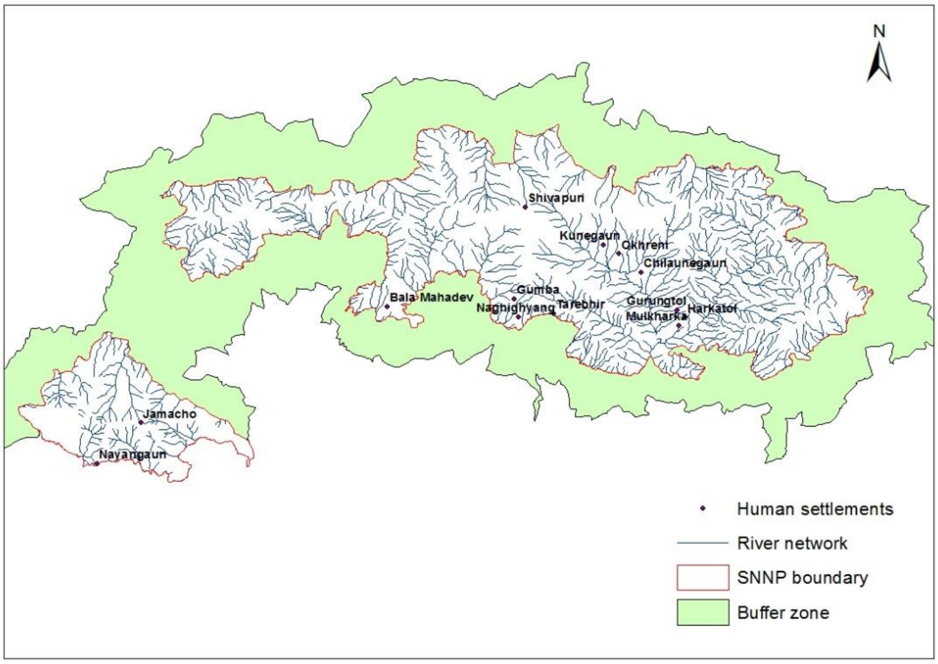


Figure 5-4: Designated buffer zone around the SNNP catchment (Source: DNPWC, 2012)

Due to strict conservation regulations (implemented by the Department of National Park and Wildlife Conservation), many ecosystem services are denied to local people. With restricted access to agricultural land and forest resources, few other income earning and employment opportunities, little access to markets or basic services, and locations in relatively remote enclaves within the national park, the livelihood base of these communities remains weak and insecure.

5.4 Results and discussion

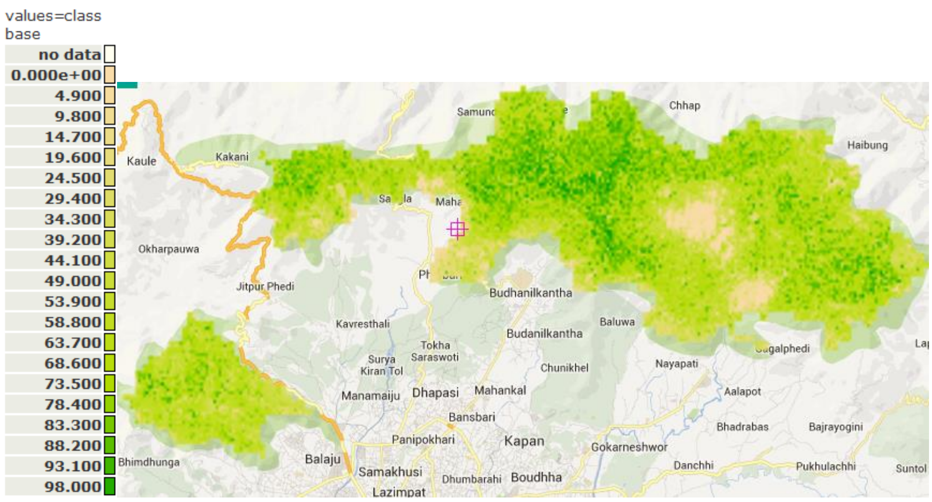
First, we assess the hydrological ESs for the entire PA catchments in detail. The study has only focused on realized hydrological ESs of the southern slopes of the PA catchments which are drained to the Bagmati River (and also a major source of drinking water supply for Kathmandu valley). Collected data and literature during the field visits are assessed in order to find out the level of water supply to downstream beneficiaries. Then, the study has focused on a sub-catchment for a detail assessment of current and future hydrological ESs using two plausible LUCC scenarios.

5.4.1 Quantifying hydrological ESs of the SNNP catchments

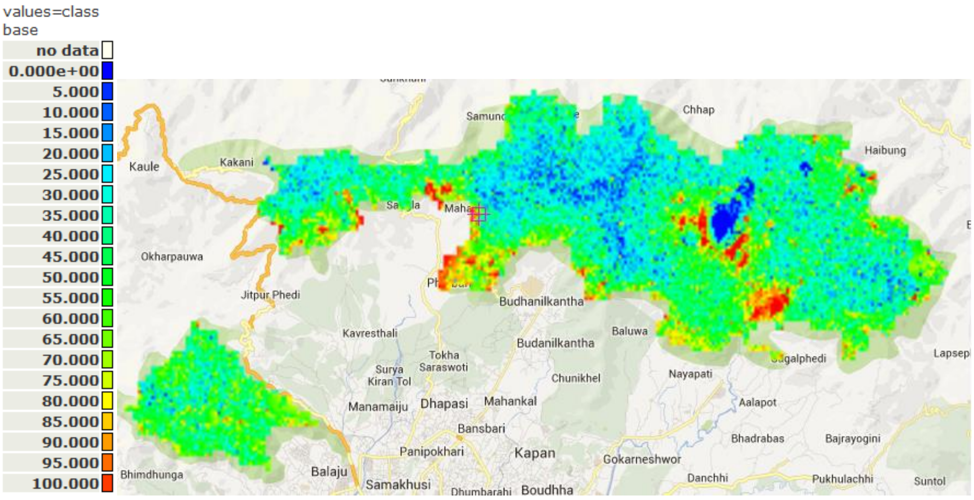
At first, the study has assessed the baseline land use and cover characteristics of the PA catchments and then it follows with the modelling of key hydrological ES. We assess annual hydrological fluxes of the PA catchments. The study also presents hydrological regulatory services provided by the PA catchments.

5.4.1.1 Land use and cover status

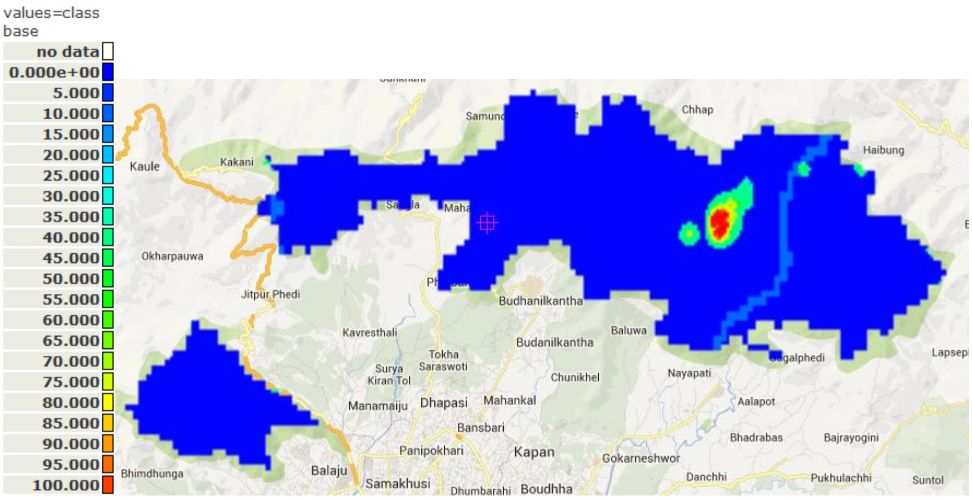
The baseline land use and cover map is derived from the globally available 30-m resolution dataset of percentage tree cover calculated by rescaling of 250-m MODIS vegetation continuous fields tree cover and cropland cover layers using circa 2000 and 2005 Landsat images (Sexton et al. 2013). The land cover of the catchment is largely dominated by tree cover (57%) (Fig. 5.5a). Herb dominated areas including croplands are concentrated in the east-central part of the Shivapuri catchment and the areas around the park's southern boundary (Fig. 5.5b). The park also hosts two upland communities where herb and bare cover percentage is relatively high. Herb cover area occupies about 41% of total catchment area. Bare covered areas represent road networks and upland human settlements (Fig. 5.5c) which cover slightly less than 2% of catchment area.



a. Baseline tree cover (mean: 57.2%)



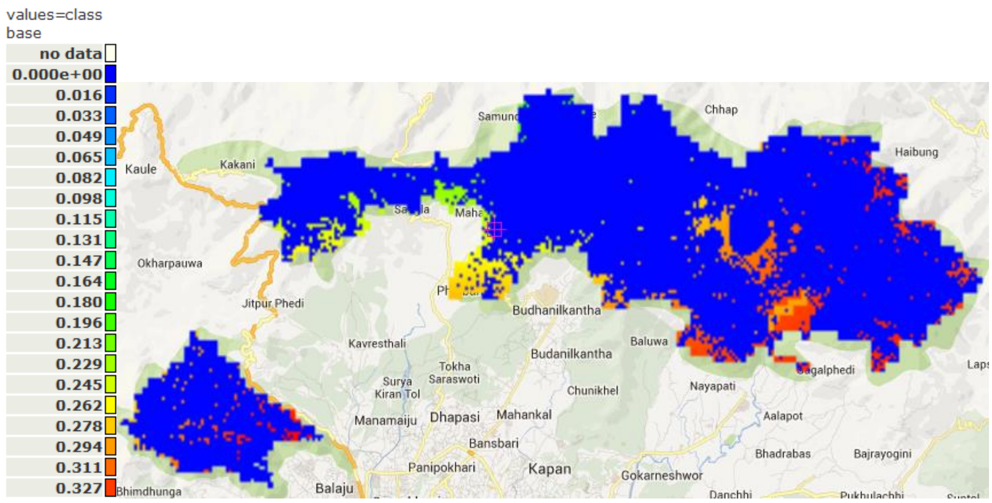
b. Baseline herb cover (mean: 41.1%)



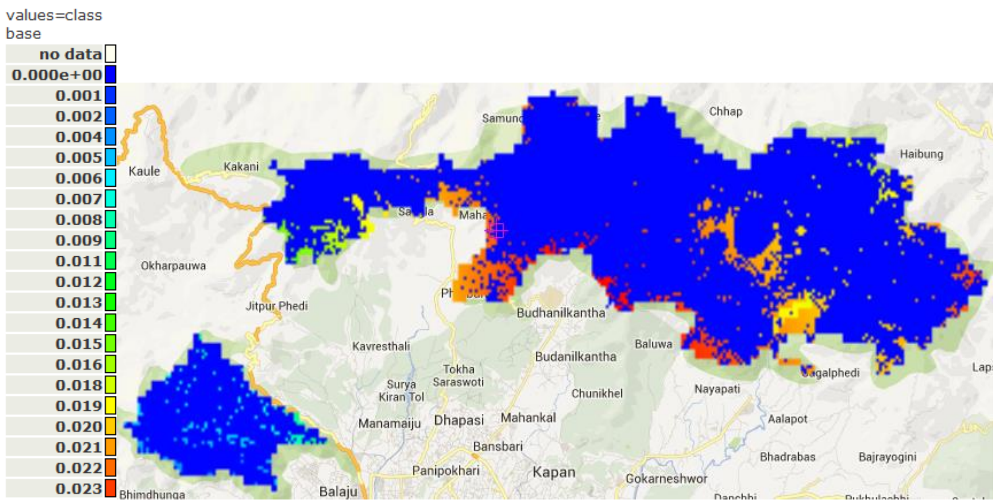
c. Baseline bare cover (mean: 1.7%)

Figure 5-5: Percentage land cover of the SNNP catchments [Source: Sexton et al. 2013)

Cropland and pasture cover areas are also located in the Sundarijal sub-catchment and surrounding areas (Fig. 5.6, below). The fraction cover of the cropland land use ranges between 0 to 0.33 and it is higher in the Sundarijal upland areas. Similarly, the pasture fractional cover is relatively low and it ranges between 0 and 0.03. Both land cover are part of herb cover.



a. Crop cover fraction (0-1)



b. Pasture cover fraction (0-1)

Figure 5-6: Major herb cover fraction in the catchment (Mulligan, 2013a based on Ramankutty et al., 2008)

The baseline land cover scenario confirms the higher dominance of tree and herb cover. As the park is located in a densely populated mountainous area, human encroachment in human dominated upland area and southern border of the park is relatively high. Such land use system may have direct impact on hydrological ESs. Using this land cover setting, the study first estimates the baseline hydrological ESs. Then, we use two plausible LUCC scenarios in the Sundarijal sub-catchment area for the detail understanding of the hydrological ESs in different scenarios.

5.4.1.2 Modelling baseline hydrological ESs

First, annual water budget is calculated with WaterWorld using the default SimTerra database and the ground based 10 year mean precipitation data combined with Landsat land cover for the year circa 2000-2005. The list of used datasets is described in table 3.3. The study collected ground rainfall data for the 5 different local stations located within and surrounding areas of the SNNP catchments (Fig. 5.7, below). We have averaged 10 year mean monthly rainfall for the period between 2001 and 2010 (Table, 5.2, below) and calibrated it with the 50 year mean rainfall available from the WorldCLIM.

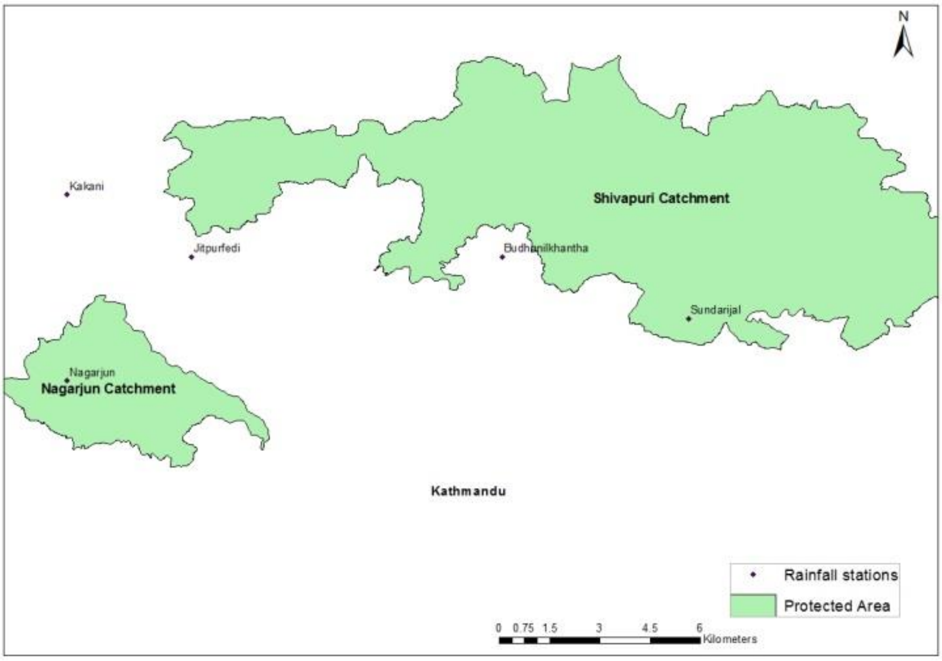


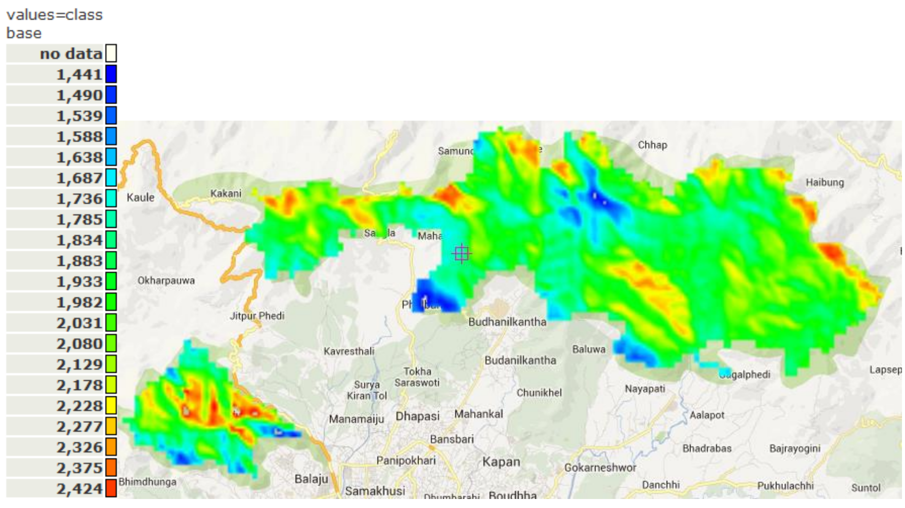
Figure 5-7: The distribution of rainfall stations within and surrounding areas of the SNNP catchments

Table 5-2: Ground rainfall data from the hydrological stations located within and surrounding areas of the SNNP catchment

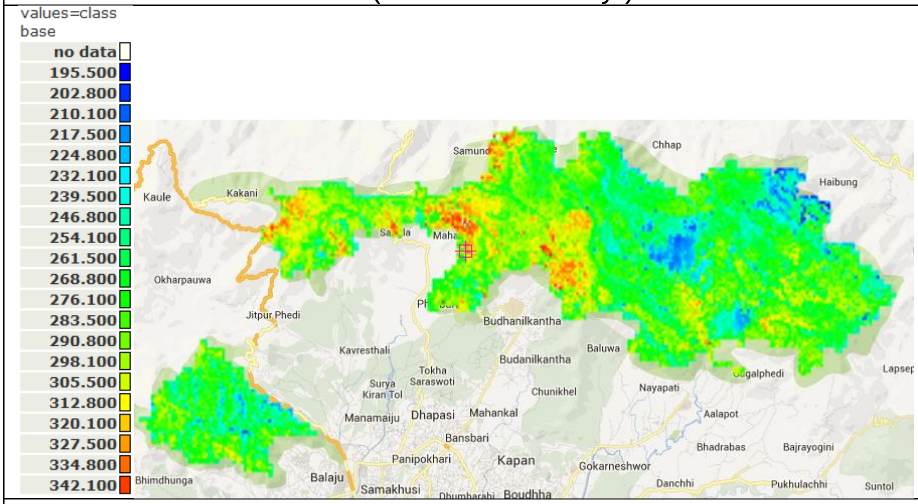
Location	Latitude	Longitude	Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average total
Nagarjun	27.75	85.25	1690	17.5	18.6	37.5	63.0	116.7	199.5	427.2	393.2	256.8	43.4	0.0	3.1	1576.5
Kakani	27.8	85.25	2064	20.1	29.5	45.6	84.6	200.2	381.2	709.3	618.4	352.6	70.5	4.1	5.8	2521.9
Jitpurfedi	27.78	85.28	1320	11.3	24.2	34.7	69.5	136.8	231.7	512.0	478.5	261.4	60.5	4.0	4.3	1828.9
Budhanilkantha	27.78	85.37	1350	11.7	18.8	34.3	81.8	201.0	287.4	560.2	496.2	271.4	59.4	2.2	5.0	2029.4
Sundarijal	27.76	85.43	1490	23.9	24.8	47.4	54.6	182.3	191.1	441.2	472.2	223.4	43.0	3.1	5.6	1712.6
Overall ground Mean				16.9	23.2	39.9	70.7	167.4	258.2	530.0	491.7	273.1	55.4	2.7	4.8	1933.9
WorldClim mean				12.2	9.9	32.9	55.4	106.2	362.6	572.1	636.6	302.2	68.8	6.2	2.3	2167.3
Fractional difference between WorldClim and ground mean				0.72	0.43	0.82	0.78	0.63	1.40	1.08	1.29	1.11	1.24	2.31	0.48	1.12

(Source: DHM, 2011 and Hijmans et al., 2005)

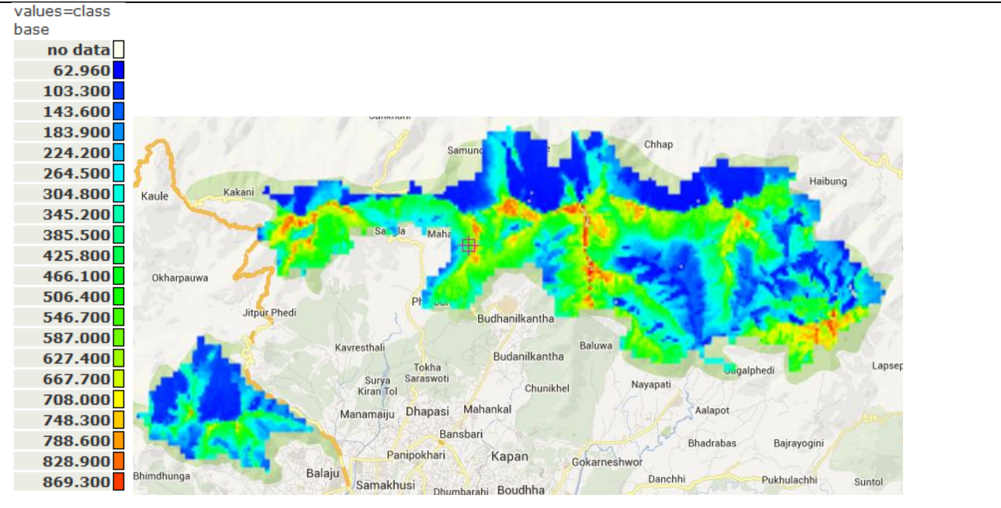
The SNNP catchment receives an annual rainfall of approx. 1930 mm/yr. There is relatively higher rainfall in some parts of the catchment which is largely contributed by wind-driven rainfall (Fig 5.8a). Similarly, the total fog input is high in forest dominated areas. The park has an average of 270 mm/yr fog input. The north-western part of catchment receives relatively higher fog inputs (Fig. 5.8b). The SNNP catchment receives only rainfall and fog input. Similarly, annual average AET is about 315 mm/yr and it is relatively high in along the mountain tops and southern slopes as these areas receives higher and persistent solar radiation (Fig. 5.8c). Finally, the annual water balance is the amount of water calculated as rainfall plus fog and snowmelt inputs minus actual evapotranspiration. The average water balance for the SNNP catchments is about 1885 mm/yr which is the amount of water available for various hydrological ES within and in the downstream areas (Fig. 5.8d).



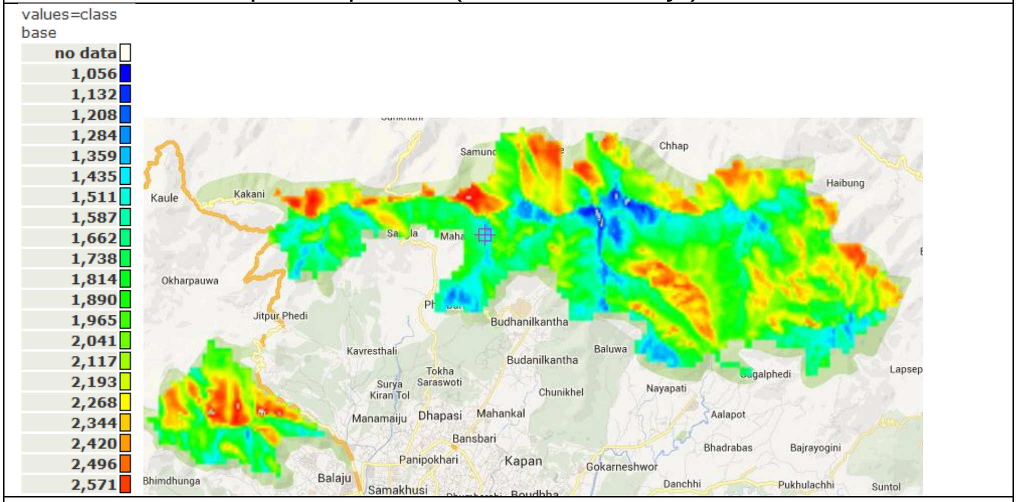
a. Wind driven rainfall (mean: 1930 mm/yr)



b. fog interception (mean: 270 mm/yr)



c. Actual evapotranspiration (mean: 315 mm/yr)

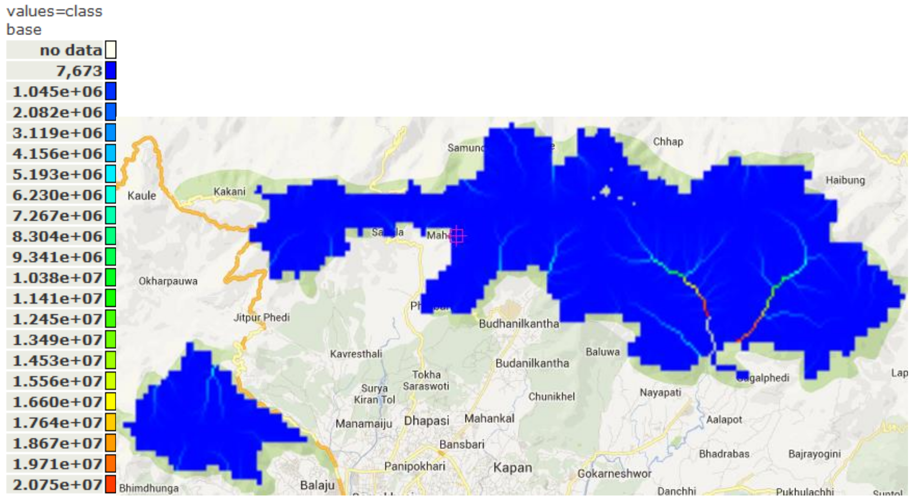


d. Water Balance (mean: 1885 mm/yr)

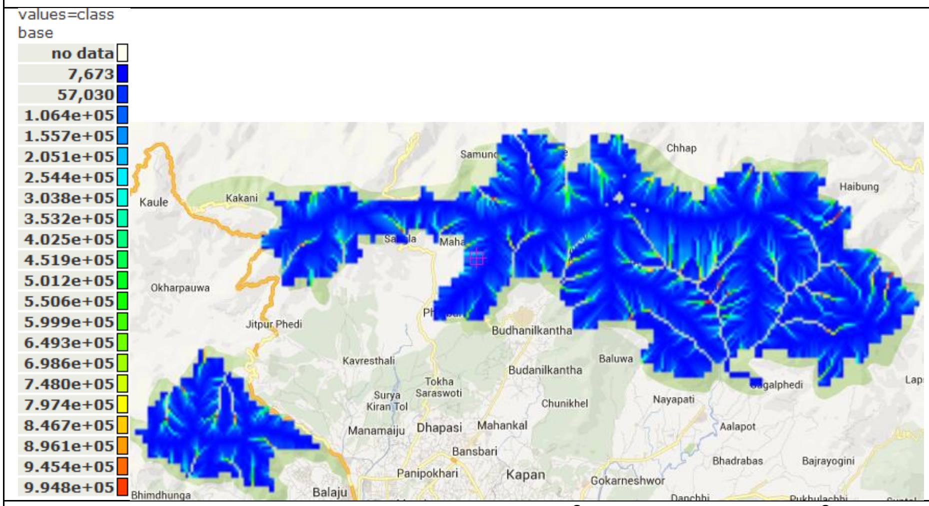
Figure 5-8: An estimation of major baseline hydrological fluxes of the SNNP catchment (WaterWorld-V2, 2013)

The modelling results show that wind driven rainfall is generally higher on east facing slopes due to the monsoon wind which comes from the east and south-east direction. Fog interception is higher on the west and in densely tree covered areas. AET shows a strong relationship with slope and exposure to solar radiation as well as forest cover. It is higher in the mountain tops and the southern slopes as these areas are directly exposed to solar radiation. Water balance is largely a function of rainfall but also shows the effects of the other fluxes.

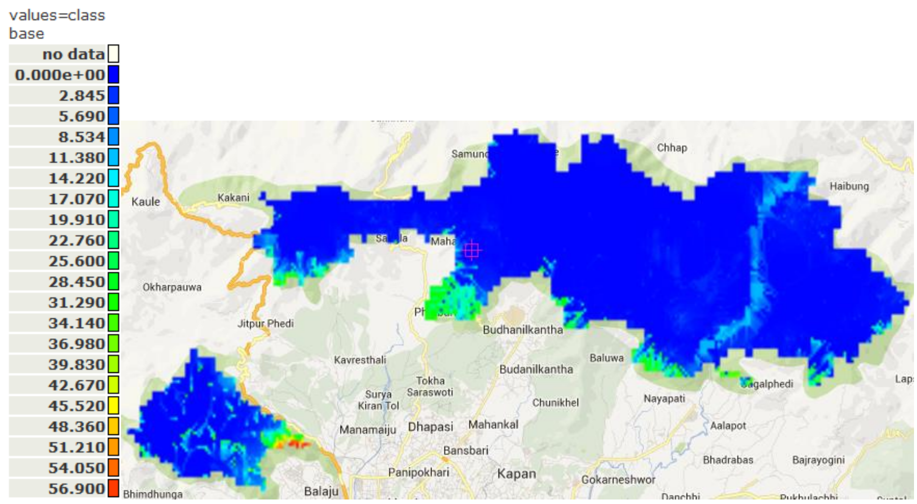
The study has also assessed the hydrological regulatory ESs provided by the catchments. Fig 5.9a shows mean annual runoff of the area and the Fig 5.9b shows the mean annual hill slope runoff. There is a low level of human footprint on hydrological ESs since the most of the PA catchment is under strict conservation practice (Fig 5.9c). There is higher level of human footprint around the park edges especially along the southern borders and areas close to a road network (passing through the eastern part of the Shivapuri catchment). Similarly, mean annual total gross soil erosion is about 14 mm/yr which is largely contributed by the human dominated upland areas in the Sundarijal sub-catchment (Fig. 5.9d).



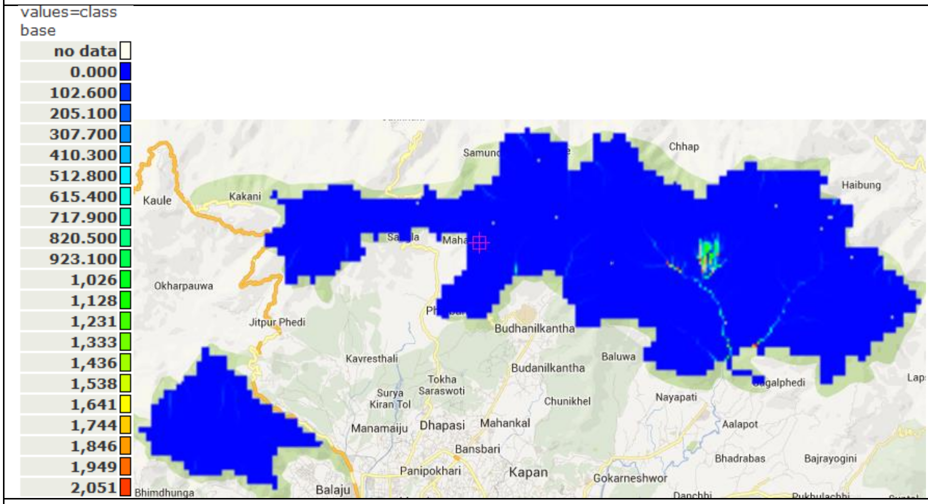
a. Total annual runoff (m^3) [mean: 198,000 m^3]



b. Total annual hill slope runoff (m^3) [mean: 69,000 m^3]



c. Human footprint on water quality (% contamination) [mean: 2.4%]



d. Annual total gross soil erosion (mm/yr) [mean: 14 mm/yr]

Figure 5-9: Hydrological ESs provided by the SNNP catchments (WaterWorld-V2, 2013)

The baseline modelling of hydrological ESs shows that the SNNP catchments generate good quality hydrological ESs. A low level of human footprint means that there is less contamination and thus good quality water supply to beneficiaries. Clearly these analyses are highly dependent on the datasets used but these appear to be reliable with respect to the situation that can be observed on the ground.

5.4.2 Water supply related provisioning ESs

The southern slopes are the main sources of clean freshwater supply to Kathmandu since they drain in the direction of the city. The SNNP catchment provides an average quantity of 54 million litres per day to the city, and the Sundarijal sub-catchment alone supplies over 34 million litres per day to Kathmandu valley (KUKL, 2010). This water supply data is calculated based on the actual water supply by water supply company (i.e. Kathmandu Upathyaka Khanepani Limited – KUKL). It does not reflect the overall water supply capacity of the PA catchments. The actual water production capacity of the entire catchment could be several times more than this estimated water supply capacity of the KUKL. The region has played a vital role in the supply of freshwater ecosystem services to downstream areas. In addition to drinking water supply, the catchment also supports cropland irrigation in the downstream areas. The Sundarijal sub-catchment has a small hydropower facility with an annual HEP production capacity of 4,231,000 KWh.

In the year between 2008 and 2009, the SNNP has contributed about 46% of total annual water supply in the Kathmandu valley (Table 5.3). In terms of surface water collection, the SNNP's share is high with an average of 58% of the total surface water. The demand for domestic water supply is ever increasing to satisfy the growing population in the Kathmandu Valley.

Table 5-3: Average monthly water supply from the SNNP catchment (in MLD - Million Litres per day)

Water Production capacity	June/ July 08	July/ Aug 08	Aug/ Sept 08	Sept / Oct 08	Oct/ Nov 08	Nov/ Dec 08	Dec08 / Jan 09	Jan/ Feb 09	Feb/ Mar 09	Mar/ April 09	April/ May 09	May/ Jun 09	Monthly average
SNNP catchment	63.5	70.8	72.8	75.9	70.9	60.4	51.8	41.8	36.6	35.1	33.1	32.1	53.7
Surface water collection	104.3	113.2	116.4	120.3	115.5	104.4	90.2	74.9	67.4	65.6	62.9	61.3	91.4
Groundwater collection	25.9	31.4	28.0	22.7	23.4	22.4	18.6	18.6	20.4	20.6	22.9	24.9	23.3
Total water collection (surface+ ground water)	130.2	144.6	144.4	143.0	138.9	126.8	108.8	93.5	87.9	86.2	85.8	86.2	114.7
% of SNNP water on surface water	60.9	62.5	62.5	63.1	61.4	57.9	57.4	55.8	54.3	53.5	52.6	52.3	57.9%
% of SNNP water on total water supply	48.8	49.0	50.4	53.1	51.0	47.6	47.6	44.7	41.6	40.7	38.6	37.2	45.9%

(Sources: KUKL, 2010)

Currently, average daily freshwater demand is about 350 million litres per day (MLD), which is almost 4 times higher than KUKL's average water production capacity (Fig. 5.10, below) (KUKL, 2012). So, there is a huge shortage of water supply. The increased demand is caused by the higher rate (around 5%) of annual population growth in Kathmandu valley (NTNC, 2009 and CBS, 2012).

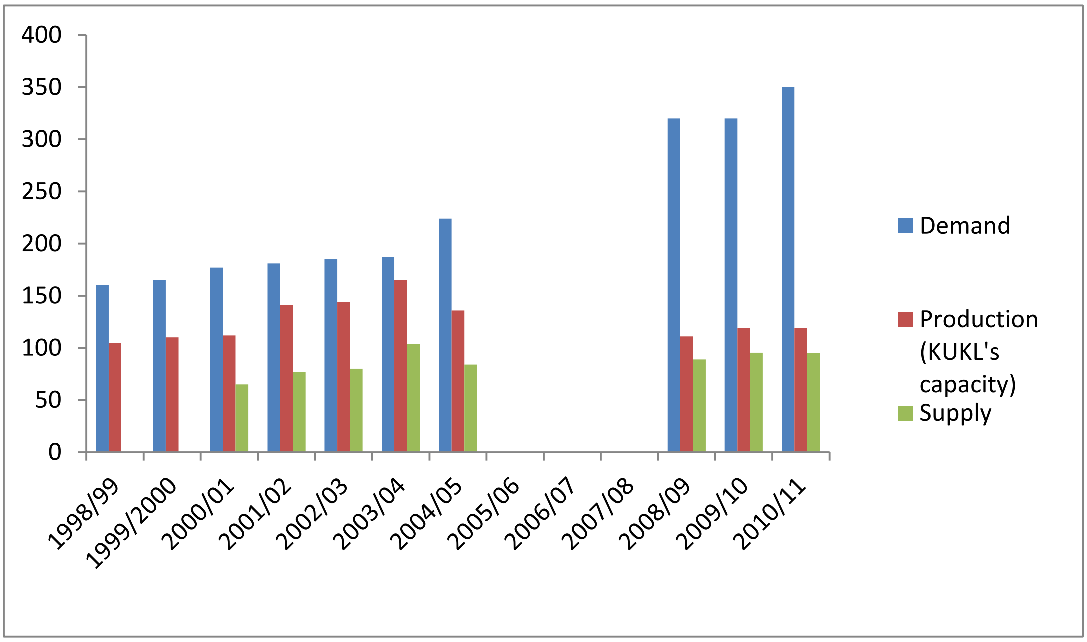


Figure 5-10: Average water demand, production and supply trends of the Kathmandu valley (MLD - Millions litres per day) (Sources: (NWSC 2002&2006 and KUKL, 2010, 2011 &2012)

The demand, production and supply trend trends show that the SNNP catchments are the major water sources for the Kathmandu valley. Due to unprecedented level of population growth, the demand for good quality water supply is ever increasing in the downstream urban area. Fig 5.11 shows the major water distribution pipelines and thus the geographical proximity of major beneficiaries from the SNNP. Some benefits are also reached beyond the downstream areas for example, the HEP related services of micro-hydropower, which benefits people across the country (via connecting to national grid line).

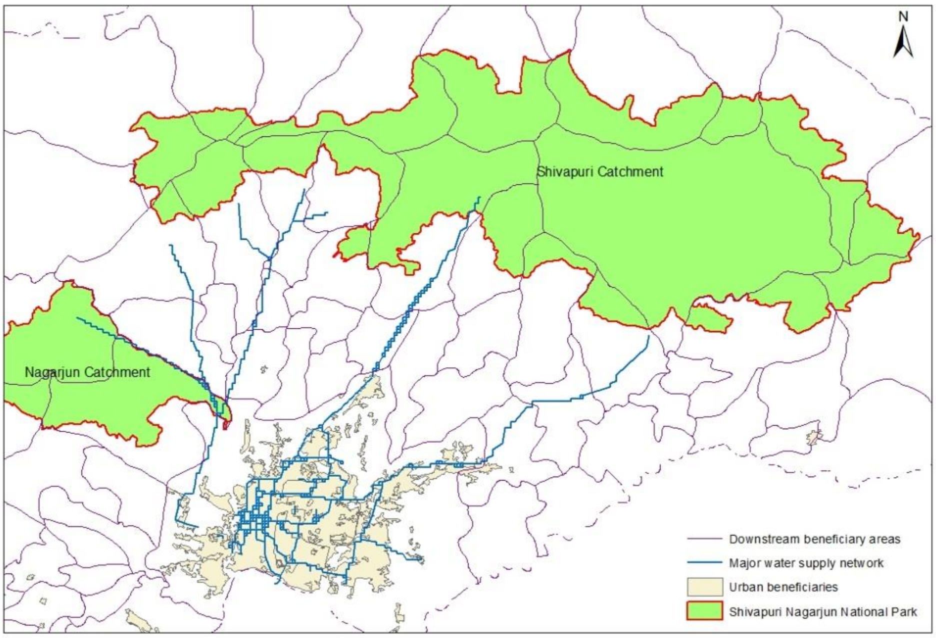


Figure 5-11: Water supply pipelines and the main beneficiary areas in the downstream basin (Source; KUKL, 2012)

Recently, it has been estimated that a net financial value-added across different water uses in Kathmandu totals about US$7.65 million annually (Emerton and Iftikhar, 2006). The Sundarijal sub-catchment provides freshwater services with an average economic value of US$112/ha/yr, which is significantly higher than the world average (Maskey, 2008). The population of Kathmandu valley is about 4 million and it is rapidly increasing (CBS, 2012), so the future demand of freshwater would continue to increase in the coming years. It clearly indicates the importance of water supply related hydrological ESs provided by the SNNP catchments.

5.4.3 Assessing hydrological ESs of Sundarijal sub-catchment

The study has delineated the Sundarijal sub-catchment – a major sub-catchment of the SNNP and it is situated in the Shivapuri catchment (Fig. 5.13, below). This sub-catchment alone provides more than 35% of surface water supply to Kathmandu (KUKL, 2010). Thus, the sub-catchment has a crucial role in maintaining good water supply. The sub-catchment lies in the eastern part of the Shivapuri catchment with an approximate area of 42.47 km^2. The elevation profile of the sub-catchment ranges between 1416 masl and 2679 masl with a mean elevation level at around 2060 masl (Fig 5.12).

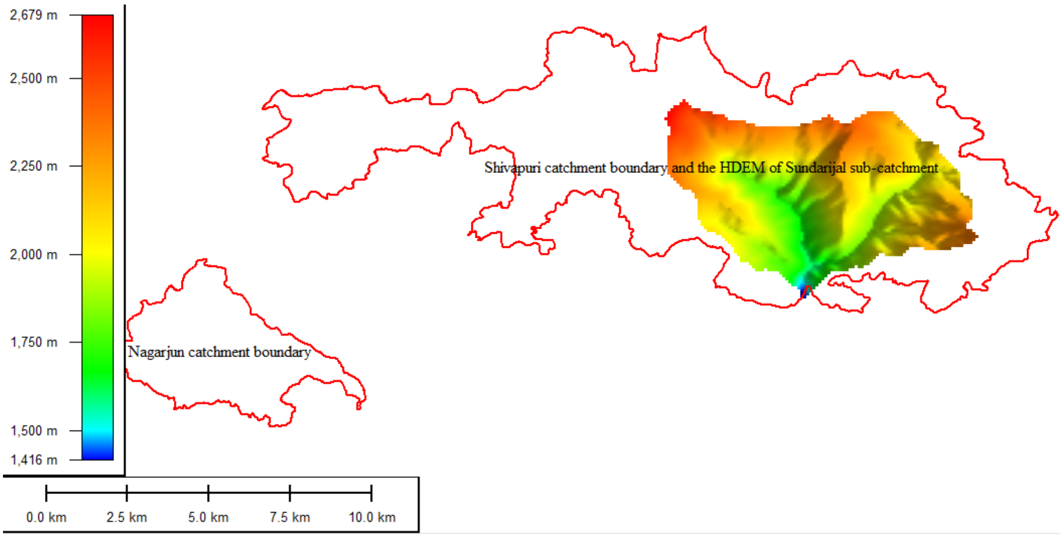
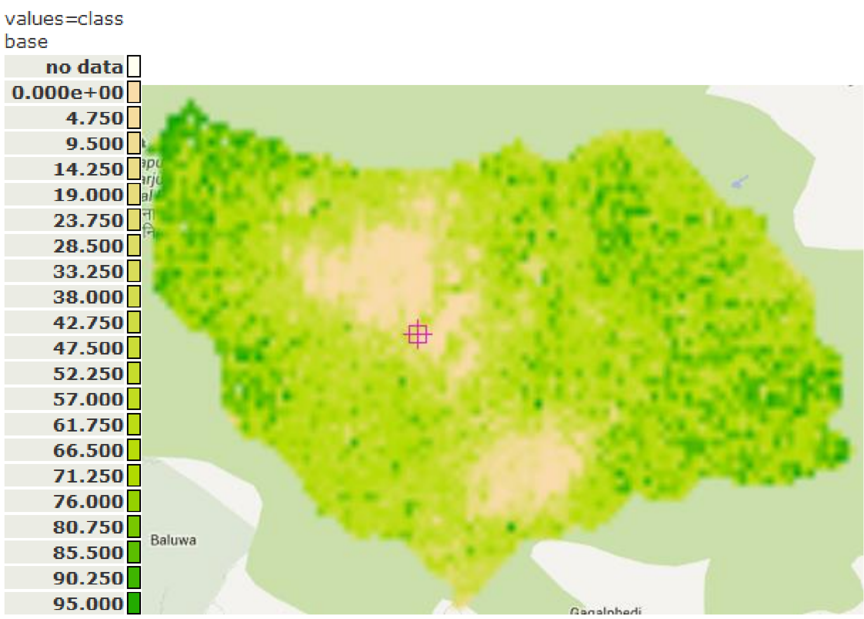
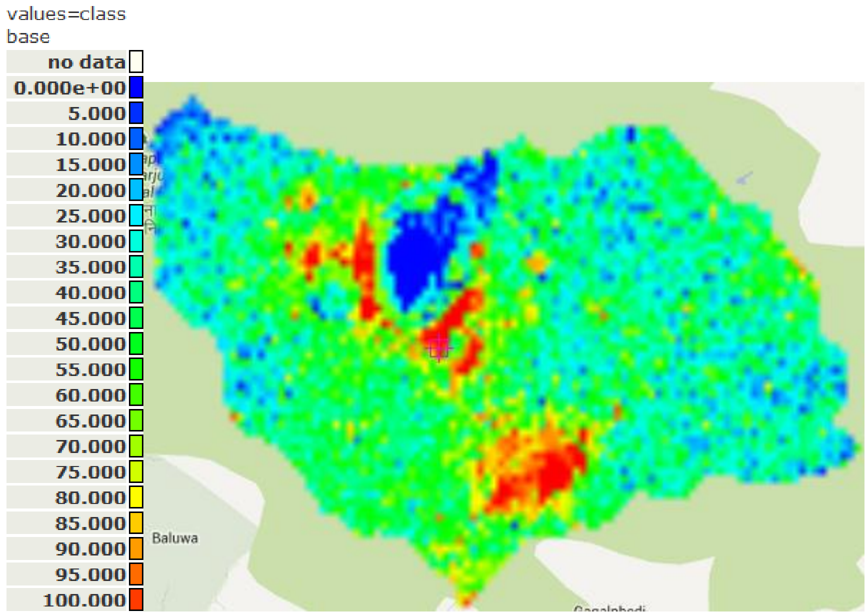


Figure 5-12: An overview of HydroSHEDS DEM of Sundarijal sub-catchment area shown within the SNNP catchment boundary (Lehner et al., 2008)

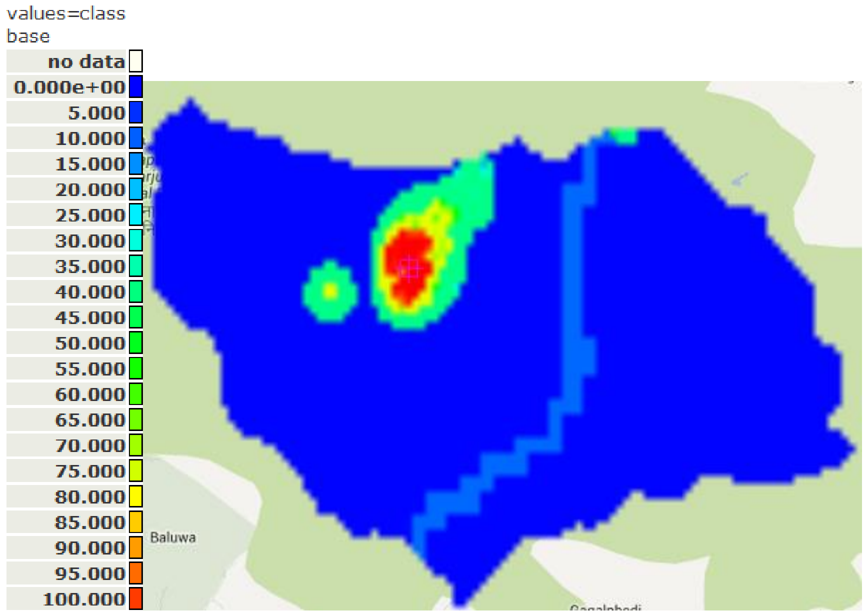
We derive a baseline land cover by using the 30-m resolution dataset of percentage tree cover by re-scaling the 250-m MODIS VCF land cover layer using circa 2000 and 2005 Landsat imagery (Sexton et al., 2013). Each raster cell of the land cover is divided into three major land use types tree, herb and bare. An average land cover of the sub-catchment is 54% forest, 41.4% herb (including cropland) and 4.6% bare (including road networks and human settlements) (Fig. 5.13, below).



a. Tree cover (mean: 54%)



b. Herb cover (mean: 41.4%)



c. Bare cover (mean: 4.6%)

Figure 5-13: Percentage vegetation coverage of Sundarijal sub-catchment (Sexton et al., 2013)

To estimate the hydrological ESs provided by the sub-catchment, the study has applied the WaterWorld PSS using the default SimTerra database for required biophysical and hydro-climatic datasets. The study also applies ground datasets such as mean monthly rainfall available from a ground station. The collected rainfall data represents the mean 17 years (between 1994 and 2010) monthly rainfall records at Sundarijal hydrological station (located at 27.46 N and 85.25 E and at altitude 1490 masl (DHM 2011). The collected monthly rainfall data has been coupled with the WorldCLIM data from SimTerra for the intended hydrological modelling (Table 5.4). The rainfall parameterization process also validates the mean annual precipitation available from the WorldCLIM precipitation data. It shows there is minimal difference between ground based mean rainfall and WorldCLIM mean rainfall.

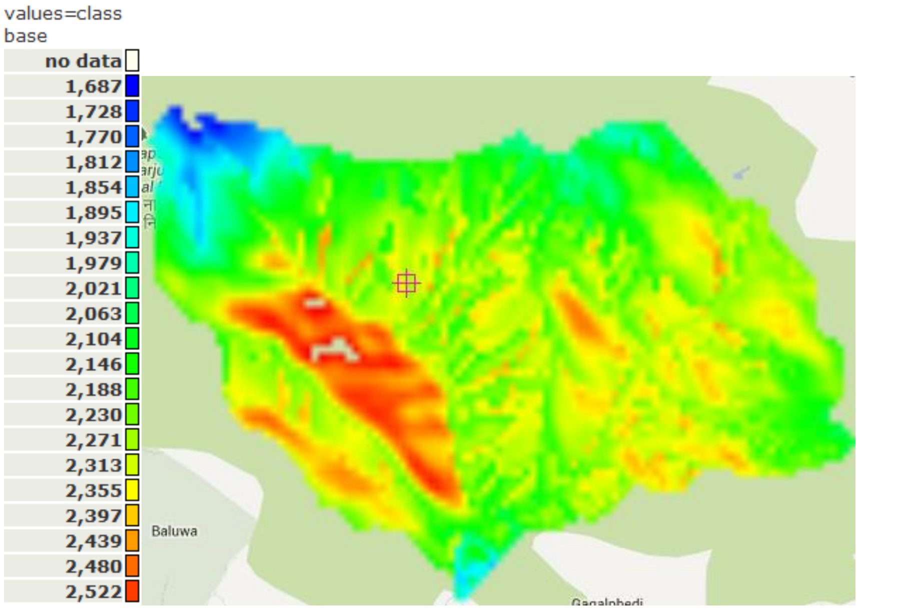
Table 5-4: Mean monthly rainfall record of Sundarijal sub-catchment (mm/month)

Sundarijal station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average total
Ground rainfall data	23.7	20.1	41.0	58.9	190.5	299.3	607.4	593.8	289.4	46.5	9.3	7.2	2187.1
WorldCLIM Mean	12.7	10.2	32.8	55.3	102.4	369.4	581.7	656.3	303.0	69.9	6.2	1.4	2201.3
Fractional difference between ground rainfall and WorldCLIM mean rainfall	0.54	0.51	0.80	0.94	0.54	1.23	0.96	1.11	1.05	1.50	0.67	0.20	1.01

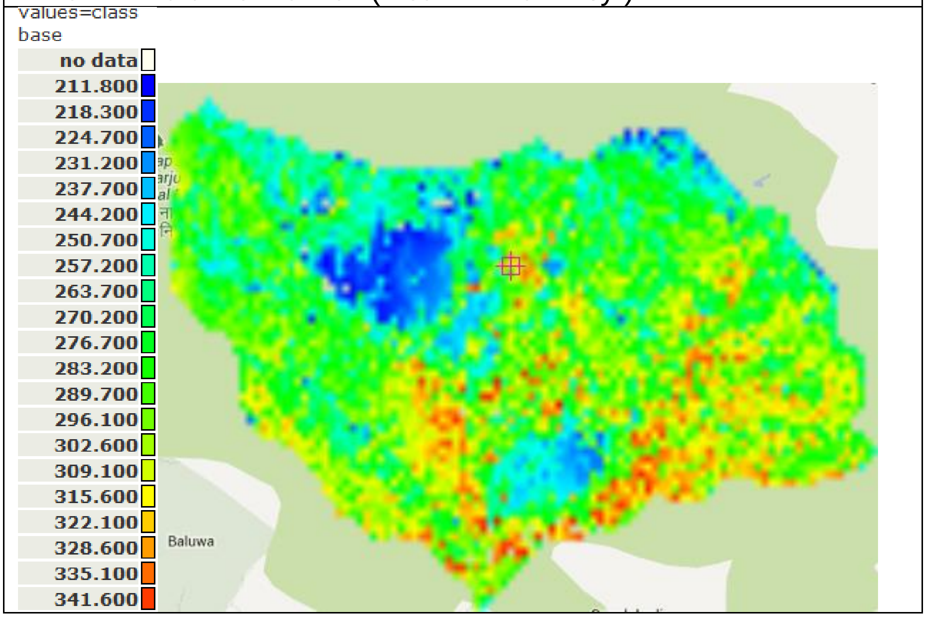
Note: Ground data represents mean 17 years of monthly rainfall between 1994 and 2010 (DHM, 2011)
Worldclim mean rainfall data represents mean 50 years of monthly rainfall between 1950 and 2000 (Hijmans et al., 2005)

There is a huge variation in monthly mean precipitation rate which is primarily affected by the wind driven monsoon rainfall, fog inputs and slope aspects. The difference between spatial and temporal scales is also clearly reflected. The monsoon period receives more than 80% of precipitation between June and September. The biggest monthly precipitation occurs in July (607 mm) and August (594 mm) and the lowest in December (7 mm) and November (9 mm). The foothills of the southern and eastern slopes receive higher rainfall compared to the mountain ridges as the monsoon wind comes from the east. The rest of the year, monthly precipitation is low and partly contributed by fog deposition/impaction characteristics which predominantly occur in the higher mountainous region.

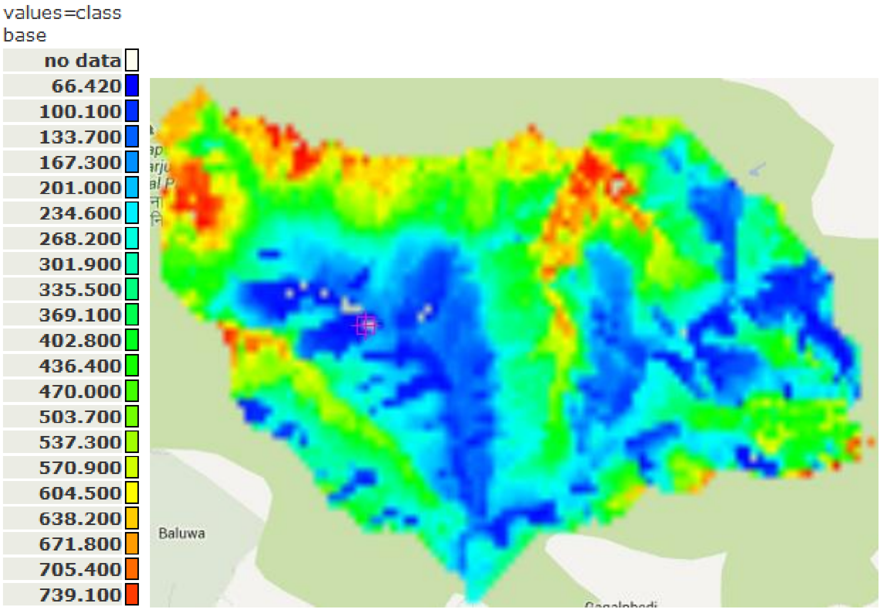
Next, the study estimates the major hydrological fluxes of the sub-catchment (Fig. 5.14, below). Average annual precipitation (mm/yr) of the area is 2,210 with an absolute minimum of 1,690 and maximum of 2,520. Water balance (mm/yr) for the area is on average 2,174 with an absolute minimum of 1,350 and maximum of 2,700. Water balance for the area (mm/month) is positive on average for all months. Actual evapotranspiration for the sub-catchment ranges from 66 to 740 mm/yr with a mean of 318 mm/yr. Fog inputs are low in relation to total precipitation at 11% on average, amounting to 280 mm/yr on average but ranging from 212 to 342 mm/yr. From that, the fog deposition contributes more than 90% of total inputs which ranges from 211 to 314 mm/yr with an average 265 mm/yr. Rest of the fog inputs come from the fog impaction (i.e. the level of CWI effect of the area) and it ranges from 2 to 33 mm/yr with an average of 14 mm/yr. The model calculates total fog inputs based on the FIESTA delivery model which relies on elevation and land cover characteristics (see, the WaterWorld PSS model equations in Appendix II). Ground based fog measurement practice in the middle mountainous region of the Himalayas would validate the true contribution of fog inputs, but this has not been a focus of research in this region.



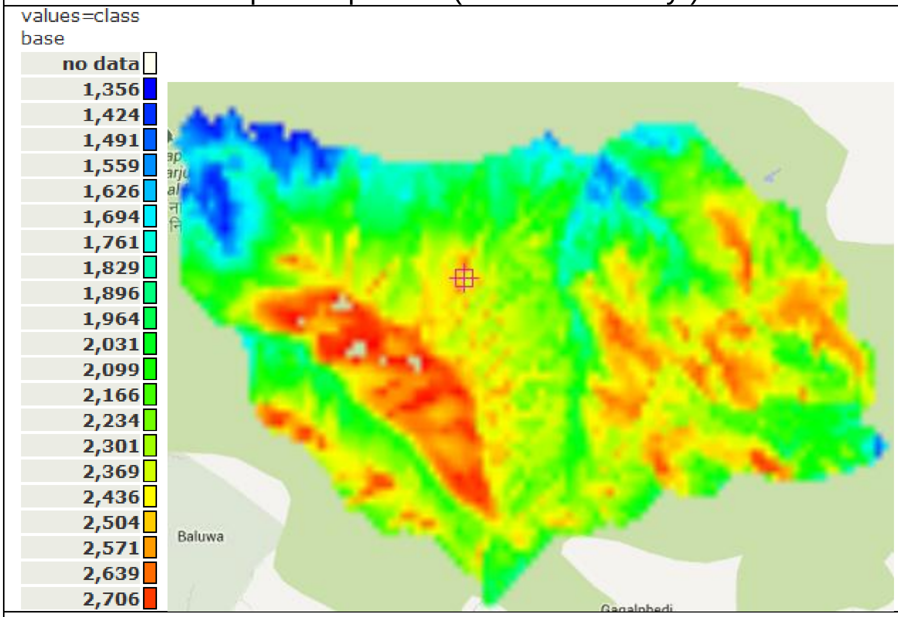
a. Wind driven rainfall (mean: 2210 mm/yr)



b. Total fog input (mean: 280 mm/yr)



c. Actual evapotranspiration (mean: 318 mm/yr)

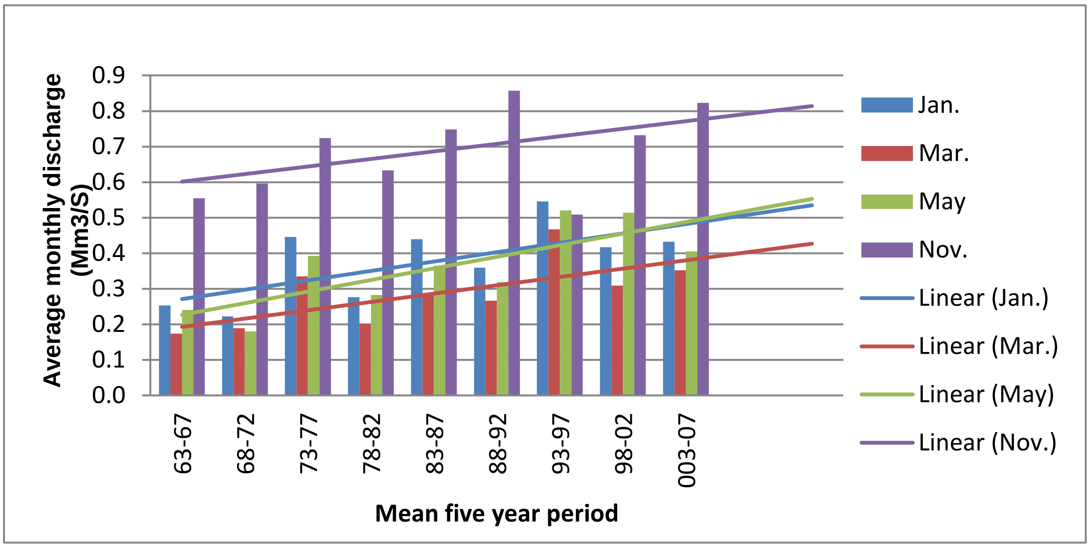


d. Water balance (mean: 2174 mm/yr)

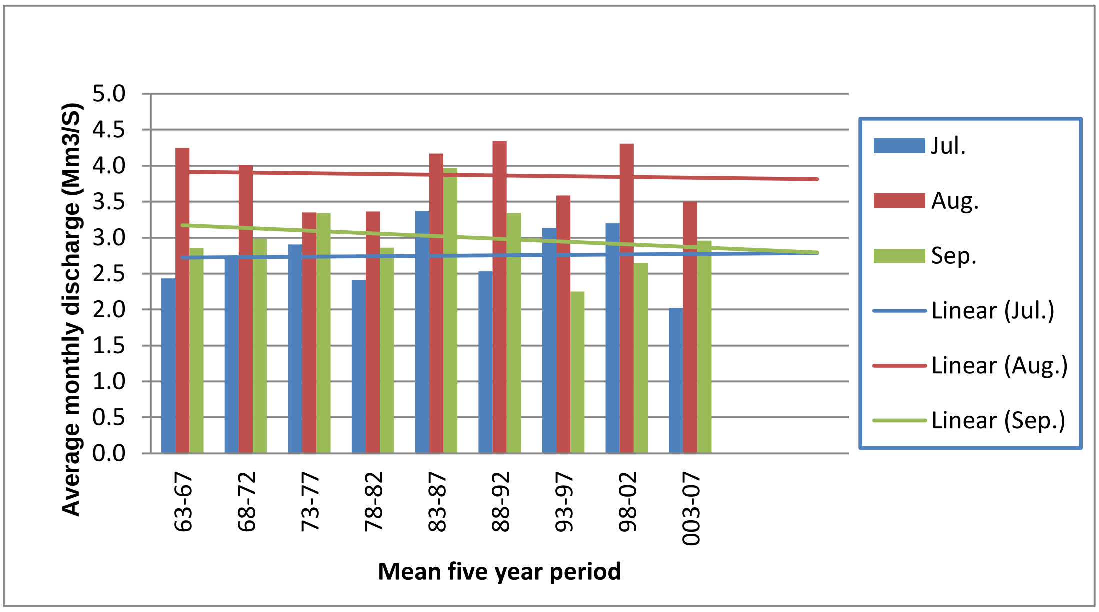
Figure 5-14: Quantitative assessment of baseline hydrological fluxes (mm/yr) (WaterWorld-V2, 2013)

In the middle mountainous region of the Himalayas, the slope aspects of the mountains play crucial role in receiving total amount of annual precipitation. There is higher amount of rainfall on the southern and eastern slopes compared to northern and western slopes. The lowest annual rainfall is seen on the north-western part which is mountain top area where wind speed and its direction may have affected the total amount of rainfall. Fog input is distributed based on the forest cover and the topographic exposure of the mountains. The AET shows a strong relationship with forest cover and also slope aspect whilst the pattern of water balance is largely a function of rainfall.

The study also assesses the mean river discharge of the Sundarijal sub-catchment between 1963 and 2007. The river discharge station is located at 27.48N Latitude and 85.25E Longitude (DHM, 2011). We have analysed five year mean discharge [data from where] to understand the change in water availability for the downstream areas. The mean river discharge shows the gradual increase in dry season river discharge but the wet season flow seems stable over the period (Fig, 5.15, below). Since the dry season expands eight months from October to May, we have assessed four alternate months for the dry season representing November, January, March and May. But for the wet season, the focus is given to July, August and September representing the major part of the wet season. The analysis shows that an increased trend in dry season flow for all four months which would be the result of positive effect of improved forest cover across the upland areas. As a result, the discharge may have been improved for the dry season period. However, the actual relation between land cover change and its influence on river discharge requires further research.



a. Mean dry season river discharge



b. Mean wet season discharge

Figure 5-15: Mean monthly river discharge [cubic millions litres per second (Mm^3/s)] at Sundarijal station (DHM, 2011)

Mean five year discharge of the Bagmati river at Sundarijal shows the small fluctuation of river flows over the last 50 years (Fig. 5.15, above). Monthly discharge for wet season shows a decreasing trend, while the mean dry season flows reveals a gradual increase. These figures suggest the beneficial impact of upland conservation /management practices implemented over the last four decades and may result from the minor impacts of afforestation on water balance because of the compensation of ET increases with fog inputs. The dry season flows may result from improved infiltration and groundwater recharge alongside increased fog inputs in the dry season under greater forest cover.

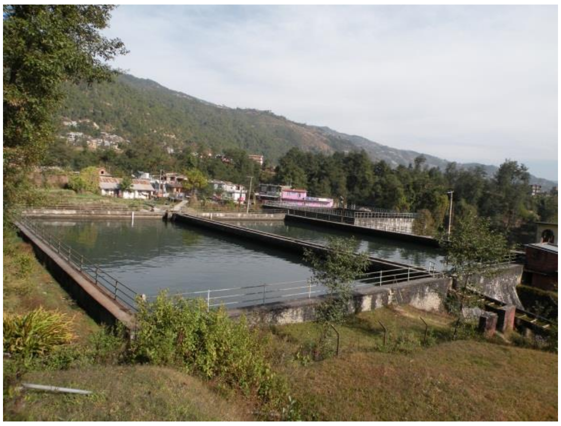
Available freshwater drained from the Sundarijal sub-catchment is mainly used for HEP generation and drinking water supply to downstream areas of the Kathmandu valley. A small hydro-dam was constructed at 27.46.18.51 N and 85.25.32.86 E to divert the catchment water for a small HEP power plant (Fig. 5.16, below). Sundarijal HEP is the second oldest HEP in the country and was commissioned in 1934. It has a total production capacity of 0.64 MW and annual energy generation capacity of 4.77 GWh (NEA, 2011).

a. Dam area　　b. Reservoir and upstream areas

Figure 5-16: The location of Sundarijal dam and reservoir site [Source; Photos taken by B. Pandeya in January 2012]

Although the available water is also used at local level for domestic uses and crop production, this study is focused on two major freshwater related ESs benefits (i.e. drinking water supply and HEP generation) both supported by the available water from the Sundarijal sub-catchment. The water is first used for HEP generation and then it is stored in reservoirs before distributing in the downstream areas (Fig. 5.17, below).

a. Water diversion for HEP generation



b. Water reservoirs for drinking water supply

Figure 5-17: Water diversion pipeline and reservoir tank for the distribution of drinking water [Source; Photos taken by B. Pandeya in January 2012]

From the above assessment, it is clear that the available water resources of the sub-catchment are heavily diverted for multiple ESs benefits. Both water supply company and HEP authority are the primary beneficiaries of the available hydrological ESs as they receive the economic benefits from supplying drinking water and HEP. Actual consumers especially drinking water users in the downstream are also benefiting from the better hydrological ESs of the PA sub-catchment. Thus, the sub-catchment plays an important role in supplying hydrological ESs to both downstream and distant beneficiaries.

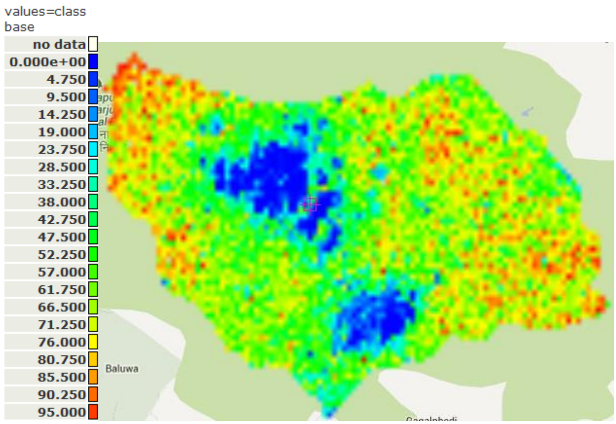
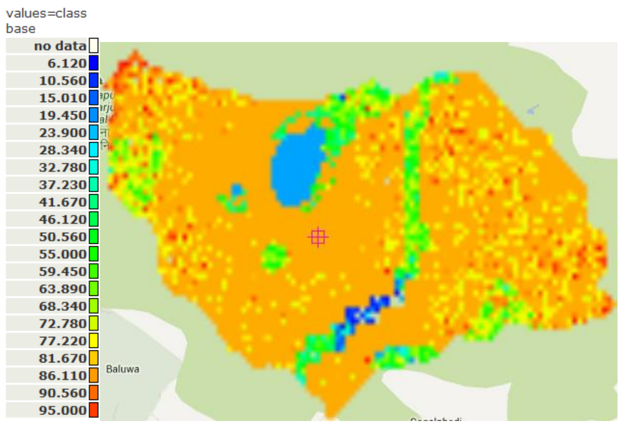
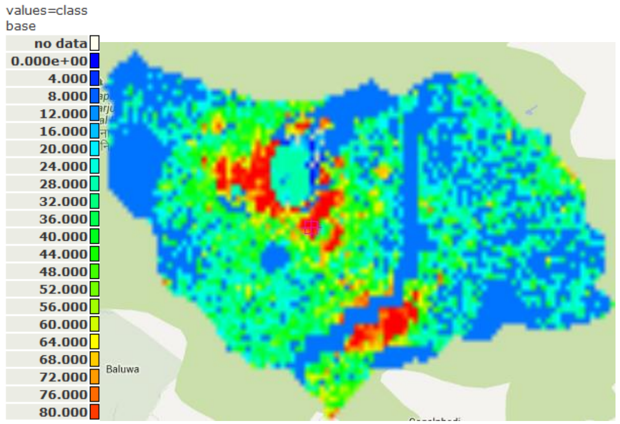
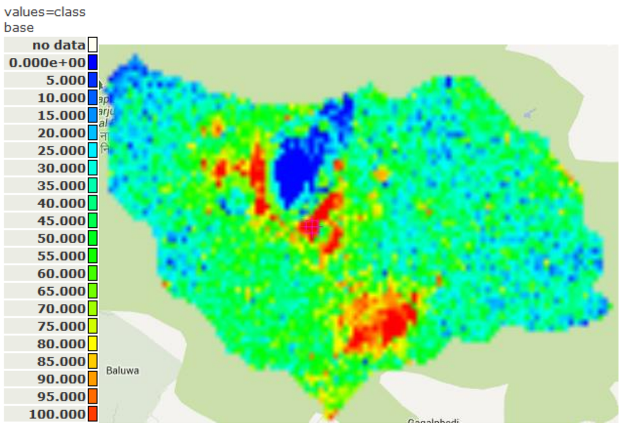
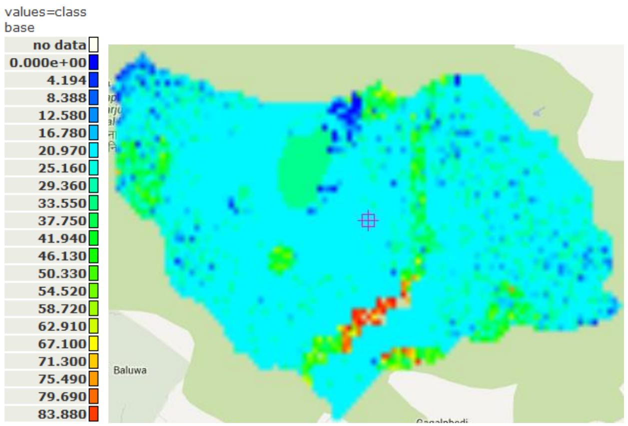
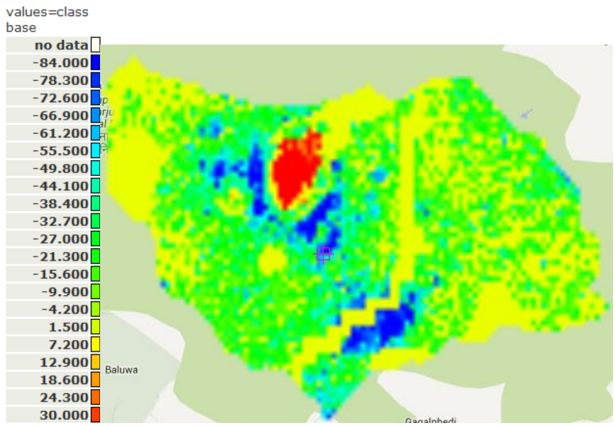
5.4.4 Modelling hydrological ESs using plausible LUCC scenarios

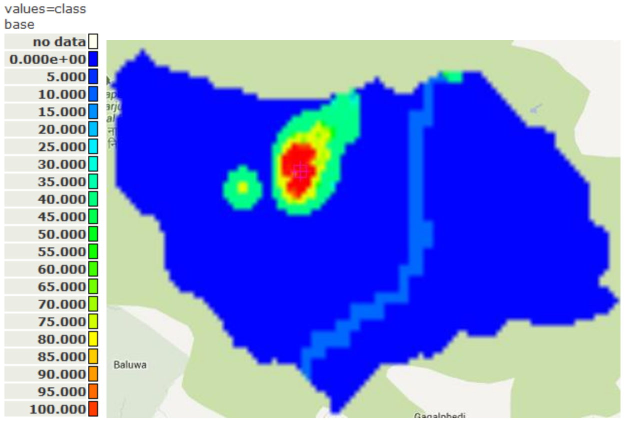
We now apply two plausible land cover and use scenarios for better understanding of hydrological ESs of Sundarijal sub-catchment. The first scenario assumes a modest forest growth with implementation of integrated watershed management programmes. Since the sub-catchment has also a significant presence of human population, it is crucial for the park authority to improve the condition of ecosystem services through better land use management practices. The second scenario assumes full control under the PA authority. Existing upland communities will be relocated outside the catchment. With this scenario, reforestation/afforestation activities will be further increased and as a result forest cover would substantially increase across the catchment. The resulting model simulations assume all other biophysical and hydro-climatic characteristics remain the same for both baseline and alternative scenarios. The description of LUCC scenarios and modelling outcomes are presented and discussed below.

'Scenario 1' – Integrated Watershed Management Approach

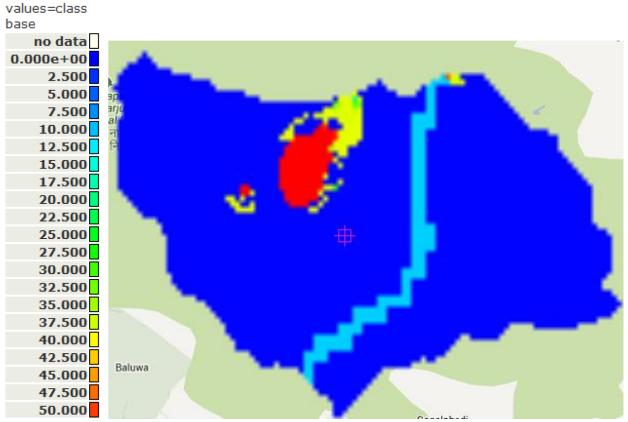
The scenario is developed based on an assumption that the human dominated upland areas will witness integrated watershed management programmes which will significantly improve the land cover of the sub-catchment. Integrated watershed management activities may include sustainable agro-forestry, improved agricultural practices and reforestation activities. Although the integrated watershed management programmes also include soil stabilization and erosion control measures, the WaterWorld model only assess the impact of LUCC changes. Reforestation activities in human dominated areas would significantly enhance forest cover across the upland areas.

The plausible LUCC scenario is applied to the baseline land cover (i.e. Landsat MODIS imagery circa 2000 and 2005 land cover). This scenario uses following set of land cover changes for the next 30 years. For 90% of the pixels where baseline herb cover is more than 30%, the new land cover percentages for the 'Scenario 1' are set as 80% tree and 20% herb cover. We have also changed the bare cover dominated area of the sub-catchment. The scenario converts 90% of herb cover area with >50% bare cover to 20% tree, 30% herb and 50% bare cover. This converts agricultural and degraded land back to forest. Percentage land cover of baseline and 'Scenario 1' land covers are presented in Fig 5.18, below.

		
a. Baseline tree cover (mean: 54%)	b. Scenario tree cover (mean: 74%)	c. Differences (mean: 20%)
		
d. Baseline herb cover (mean: 41%)	e. Scenario herb cover (mean: 23%)	f. Differences (mean: 18%)



g. Baseline bare cover (mean: 4.6%)



h. Scenario bare cover (mean: 2.8%)

i. Differences (mean: 1.8%)

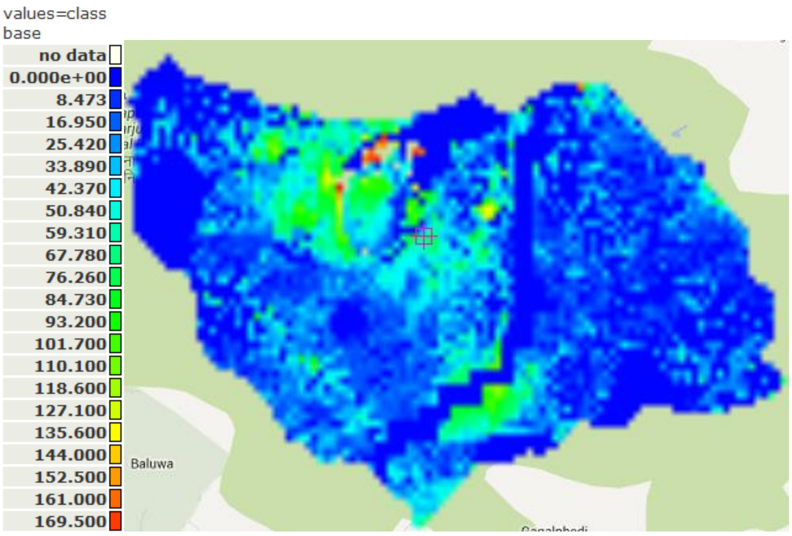
Figure 5-18: Percentage land cover changes between baseline and 'Scenario 1' land cover types

The scenario leads to an increase in tree cover of 20% on average, a decrease of herb cover of -18% on average and a decrease of bare cover of 2% on average. As a result, average tree cover increase from 54% in baseline to 74%. The herb cover percentage decreases from 41% to 23% and the bare cover will decrease from 4.6% to 2.8% of the sub-catchment.

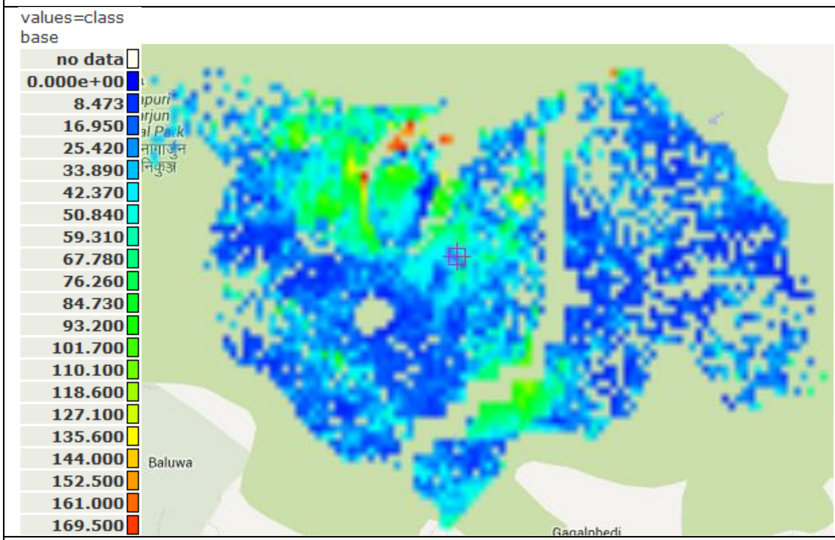
While developing such a LUCC scenario, the study has considered a best possible land cover in which the baseline forest cover may improve due to a range of watershed management programmes. Since the Sundarijal sub-catchment is a part of the SNNP, the upland areas have already exercised strictly monitored afforestation programme. With the implementation of integrated watershed management programmes, human dominated upland areas will receive direct support to manage their lands. As a result, the forest cover would increase over the next three decades.

With all other input variables held constant, this LUCC scenario leads to an area-average increase in evapotranspiration of 20 mm/yr (6.4%) (Fig. 5.19, below) and an average increase in fog interception of 20 mm/yr (7.3%) (Fig. 5.20, below) leading to an overall increase in water balance of only 0.14 mm/yr (0.007%) (Fig. 5.21, below). Thus, the area would avoid annual water loss as fog inputs are slightly greater than annual AET.

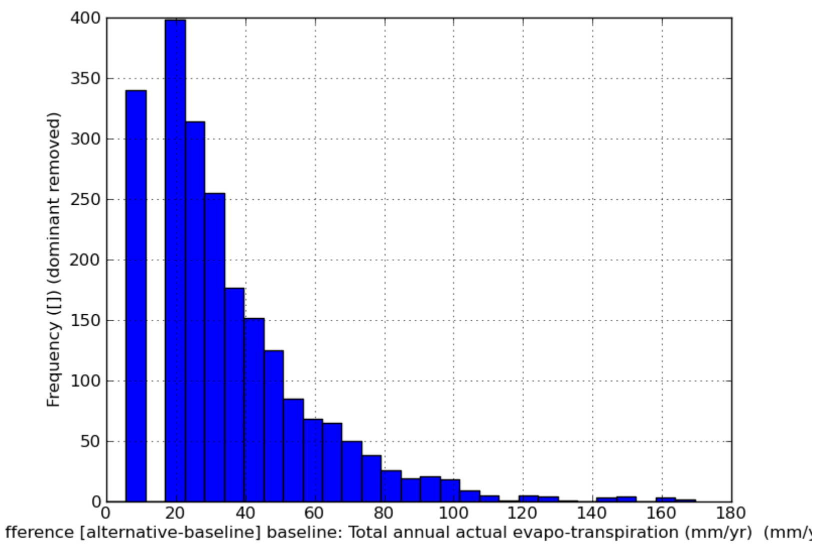
Under the integrated watershed management programme, the sub-catchment will experience higher level of AET in newly increased forested areas (Fig. 5.20a). The increase in AET will occur in previously herb and bare cover dominated areas which are concentrated in and around the existing upland human settlements (Fig. 5.20b). The distribution of actual change in AET ranges 8 to 170 mm/yr (Fig. 5.20c) and the percentage change ranges between 6% to 56% but most areas will witness a modest increase up to 20% and some areas will have up to a 50% increase (Fig.5.20d). As a whole, the AET will be increased by 860,000 m^3.



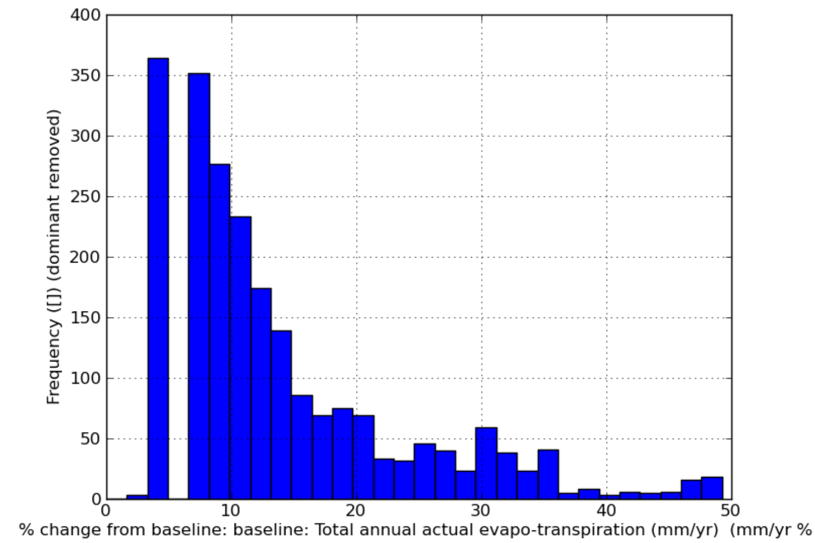
a. Actual change in AET (mm/yr) (mean: 20 mm/yr)



b. Pixels with positive change in AET (mm/yr)



c. Frequency distribution of actual change in AET (mm/yr)

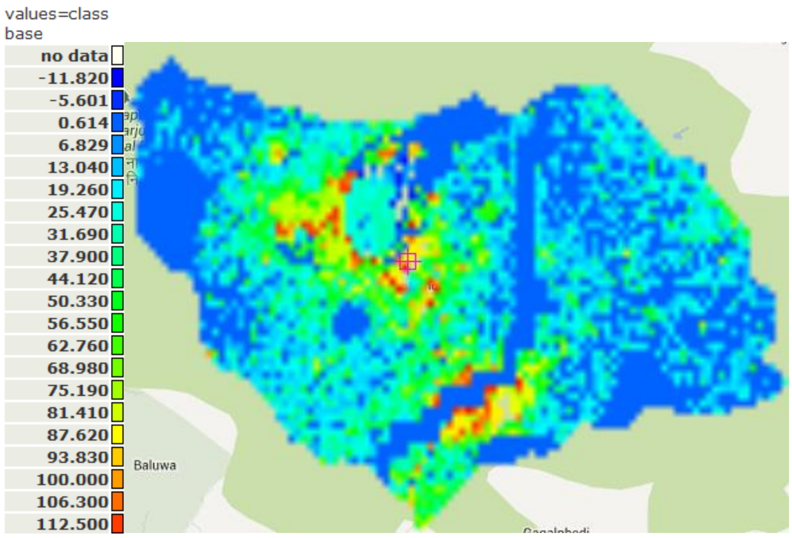


d. Frequency distribution of percentage change in AET

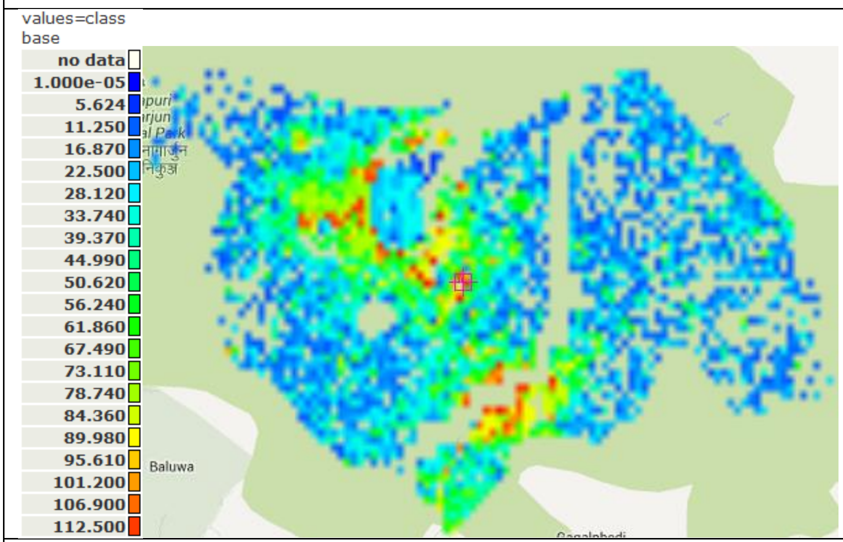
Figure 5-19: Quantitative change in annual AET ('Scenario 1' vs. baseline) (WaterWorld-V2, 2013)

Similarly, increase in fog inputs also follows the increase in forest cover. There will be higher level of fog deposition across the sub-catchment (Fig. 5.20, below). As the 'Scenario 1' expects a significant increase in forest cover in the herb and bare cover areas, there will be greater impact of forest related fog deposition. A smaller level of fog impaction also increases across the sub-catchment. The distribution of actual change ranges between -12 to 112 and the percentage change ranges from 4% to

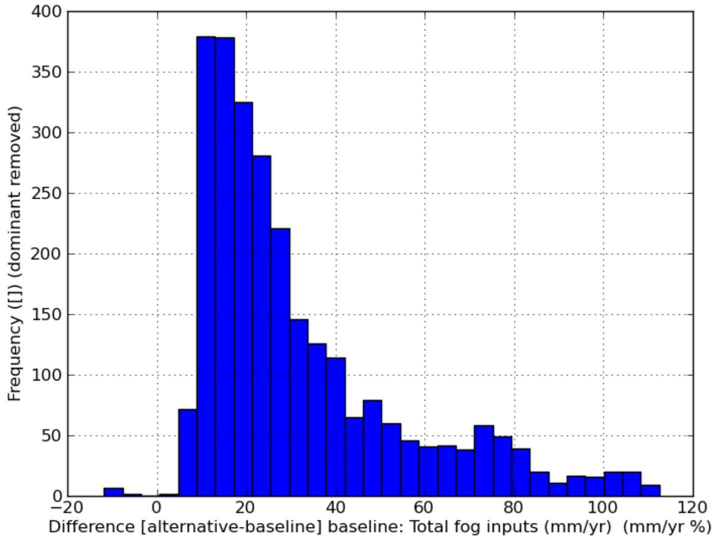
50% but most areas will receive between 10 and 35% increase in baseline fog interception.



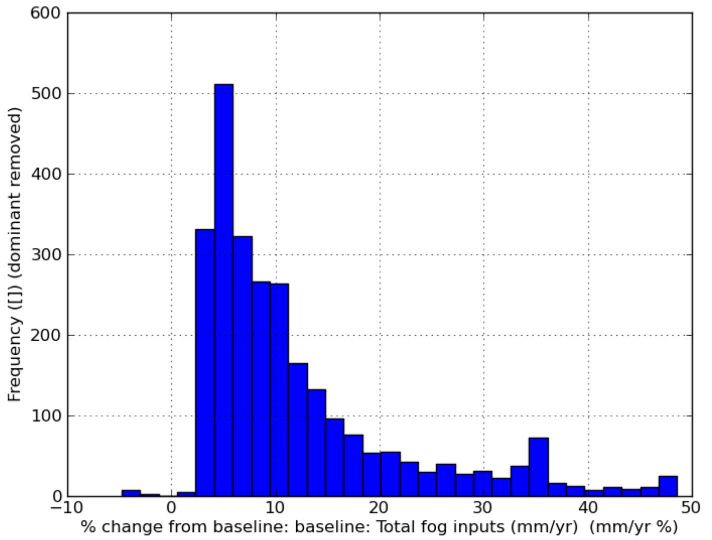
a. Actual change in fog inputs (mm/yr) (mean: 20 mm/yr)



b. Pixels with positive change in Fog Inputs (mm/yr)



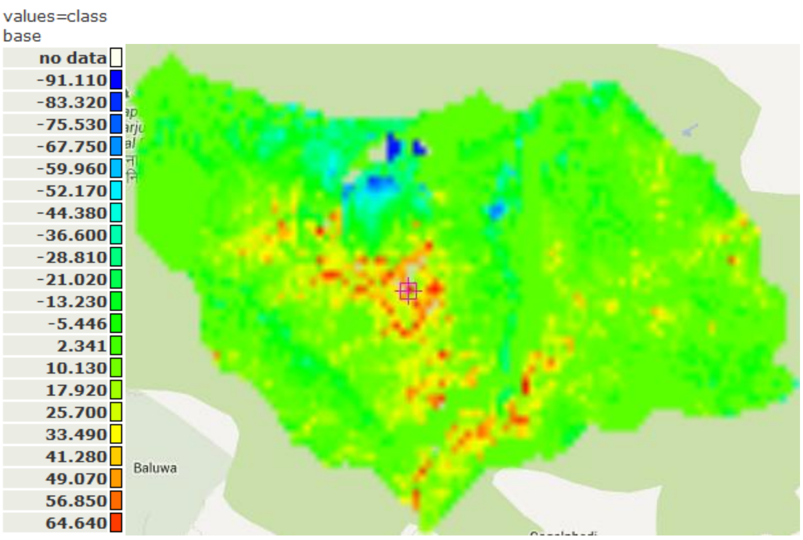
c. Frequency distribution of actual change in Fog Inputs (mm/yr)



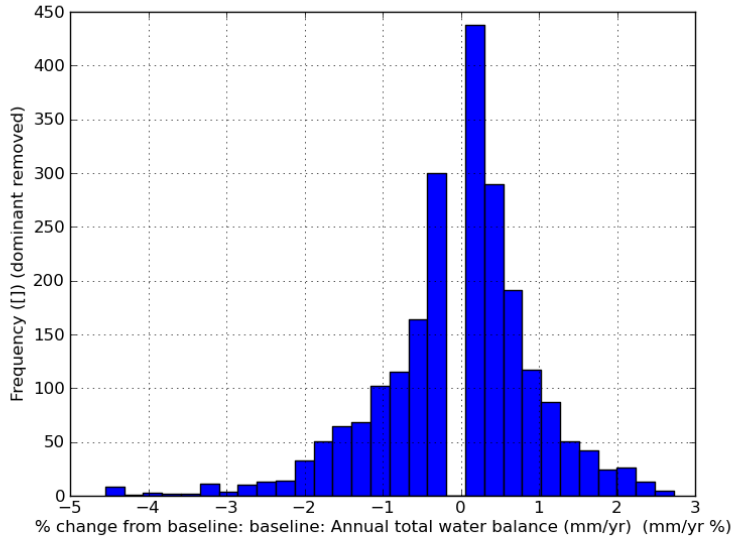
d. Frequency distribution of percentage change in Fog Inputs

Figure 5-20: Quantitative change in annual Fog Inputs ('Scenario 1' vs. baseline) (WaterWorld-V2, 2013)

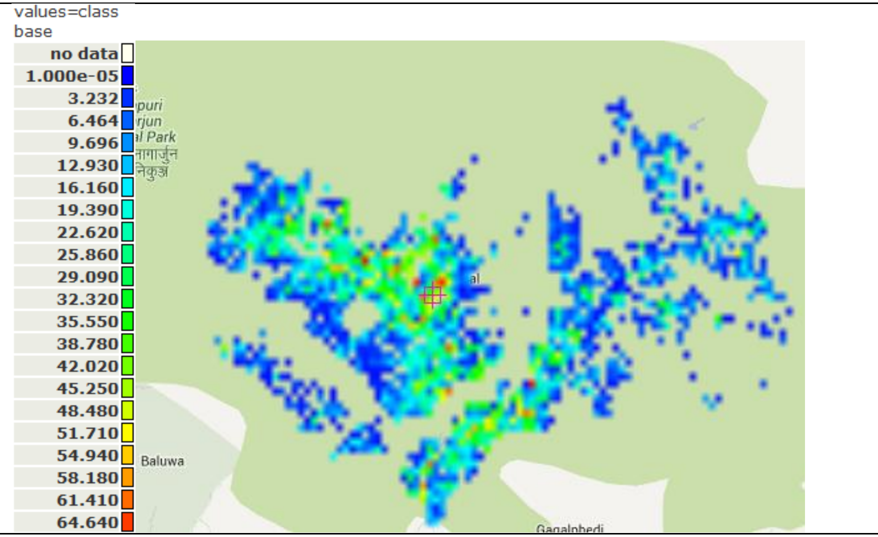
As the forest cover is increased, both evapotranspiration and fog interception processes are increased simultaneously in the newly forested parts of the catchment. The opposing effects of AET and fog interception processes have resulted in negligible change (0.14 mm/yr) in annual water balance as an area-average (Fig. 5.21, below). The annual water balance is significantly decreased in previously bare-covered areas. However, the distribution of percentage change in annual water balance ranges from -5% to 3%. In this case, parts of the sub-catchment will witness drying and the rest of the areas will have some increase in annual water balance. The increased amount of water is about 6,100 m^3 per year.



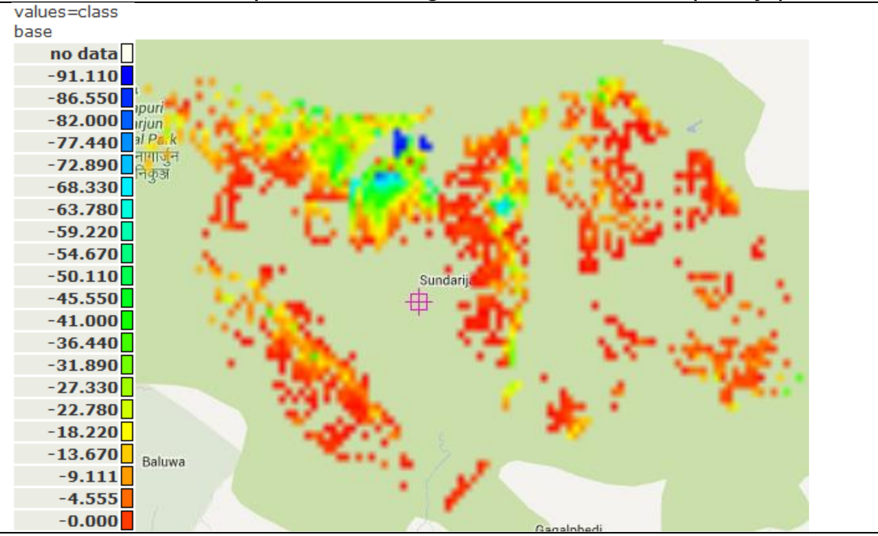
a. Actual change in water balance (mm/yr) (mean: 0.14 mm/yr)



b. Frequency distribution of percentage change in water balance



c. Pixels with positive change in water balance (mm/yr)

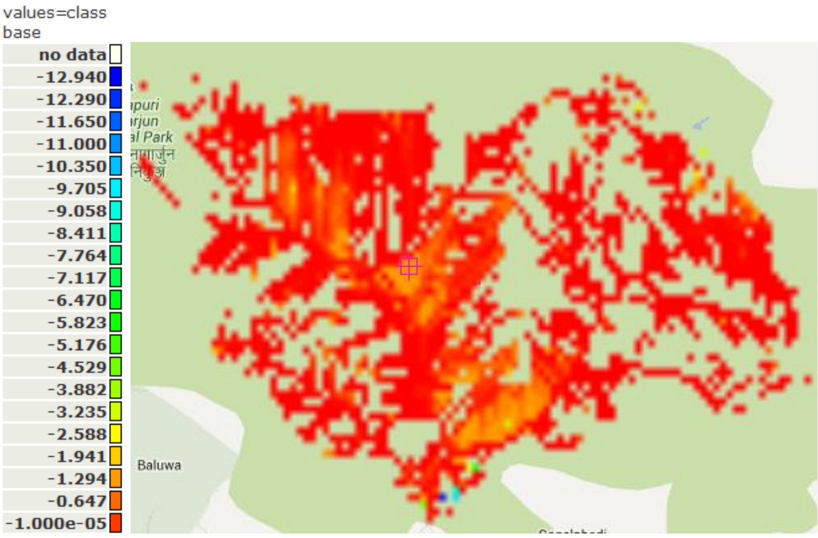


d. Pixels with negative change in water balance (mm/yr)

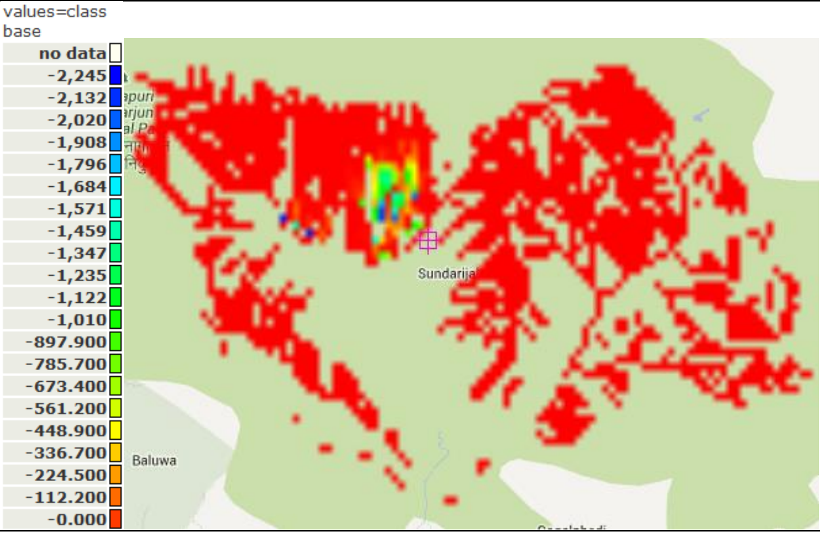
Figure 5-21: Quantitative change in annual water balance (‘Scenario 1’ vs. baseline) (WaterWorld-V2, 2013)

The modelling results show that there is a marginal increase in annual water availability which is largely due to greater inputs from the increased CWI inputs. The study findings thus highlight the role of fog inputs in the mid-mountainous region forest and their impacts on quantity related hydrological ESs.

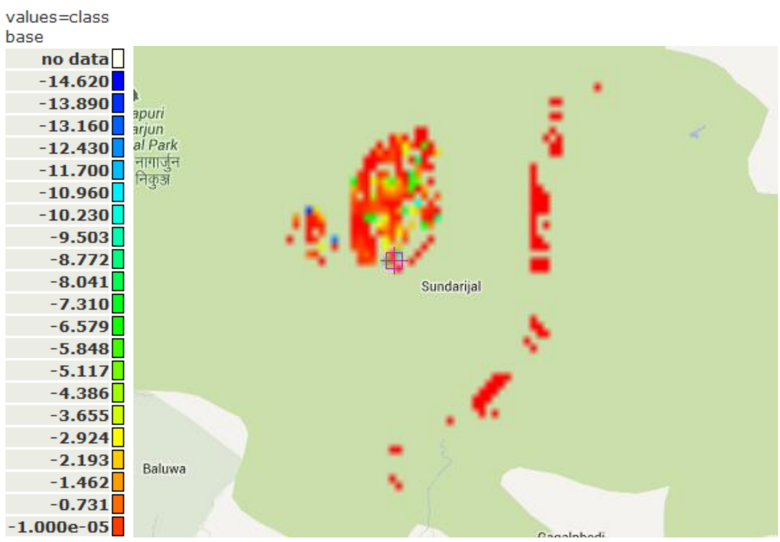
We also assess some of the quality related hydrological ESs using this ‘Scenario 1’ land cover (Fig. 5.22, below). Human footprint is decreased marginally by 0.24% on average. Human footprint was calculated based on the human interferences such as cropland, infrastructural development, human settlements (built up areas) and grazing areas. Similarly, the annual total gross soil erosion is decreased by 36 mm/yr. And the annual total hillslope net soil erosion would decrease by 0.2%. With increased forest cover, those ESs would slightly improve over the period.



a. Decrease in human footprint on water quality (% contamination) (mean: -0.24%)



b. Decrease in annual total gross soil erosion (mm/yr) (mean: -36 mm/yr)



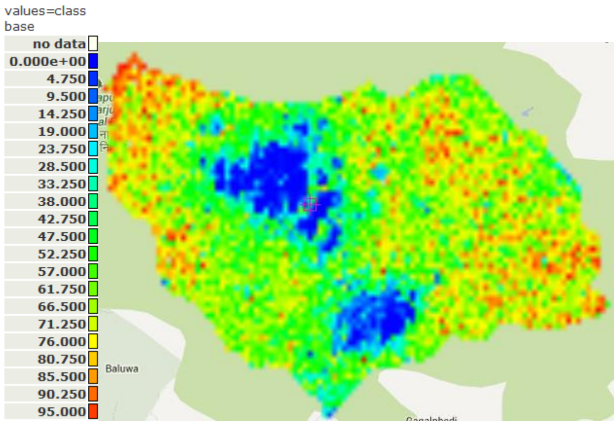
Decrease in annual total hillslope net soil erosion (mm/yr) (mean: -0.19 mm/yr)

Figure 5-22: Qualitative change in hydrological ES ('Scenario 1' vs. baseline)

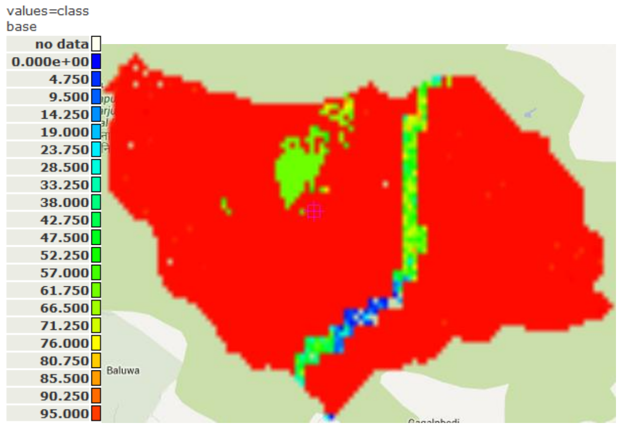
With the above modelling outcomes, the study confirms that the integrated watershed management programmes would increase some degree of hydrological ESs benefits. Although the annual water availability is not substantially changed, low human footprint and better hydrological quality services are directly benefitting downstream beneficiaries. In this situation, the main water supply company will be the primary beneficiary of such improved hydrological ESs.

'Scenario 2' - Human Resettlement and Reforestation

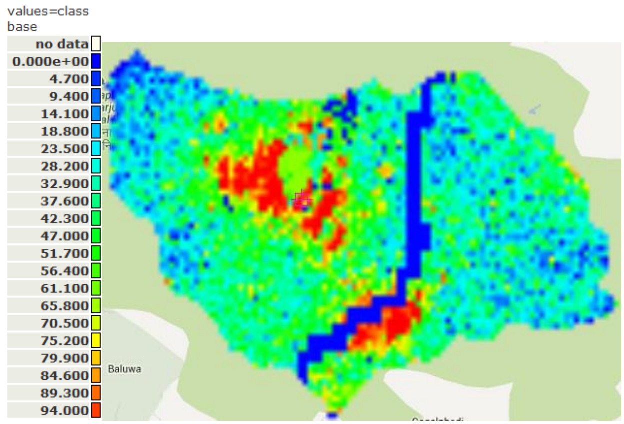
For this scenario, we simulate large scale forest regeneration in which existing bare and herb cover areas would change to forest cover. This scenario may also involve the relocation of upland communities from the sub-catchment. Using Landsat VCF (circa 2000 and 2005 land cover) imagery as baseline land cover (Sexton et al., 2013), the study has applied following land cover change scenarios. For 90% of the sub-catchment area where percentage herb cover is more than 10%, land covers are set to 94% tree and 6% herb cover. In addition, 90% of the area with herb cover of >50% would convert to 60% tree, 30% herb and 10% bare cover. The scenario will convert most of the herb and bare dominated areas (agriculture and degraded lands) in the upland areas especially in human settlements to forested areas (Fig. 5.23, below).



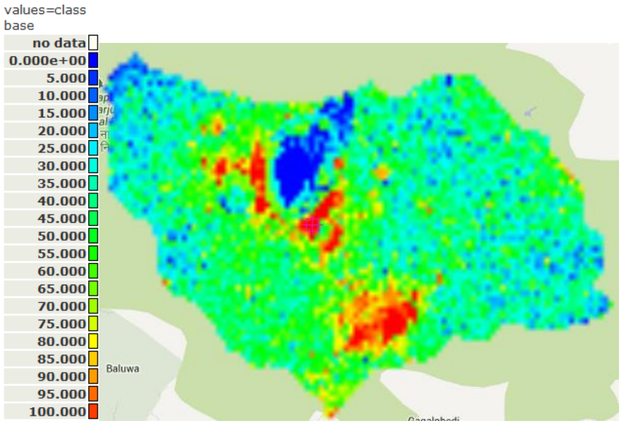
b. Baseline tree cover (mean: 54%)



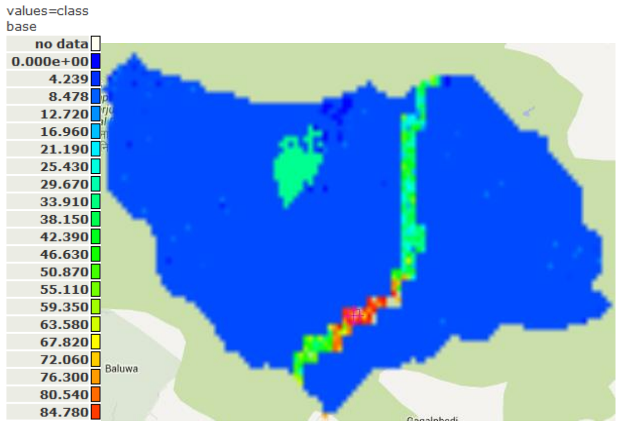
c. Scenario tree cover (mean: 90.5%)



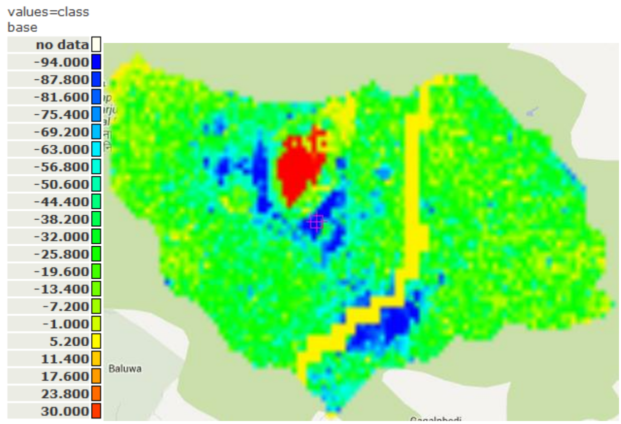
b. Differences (mean: 37%)



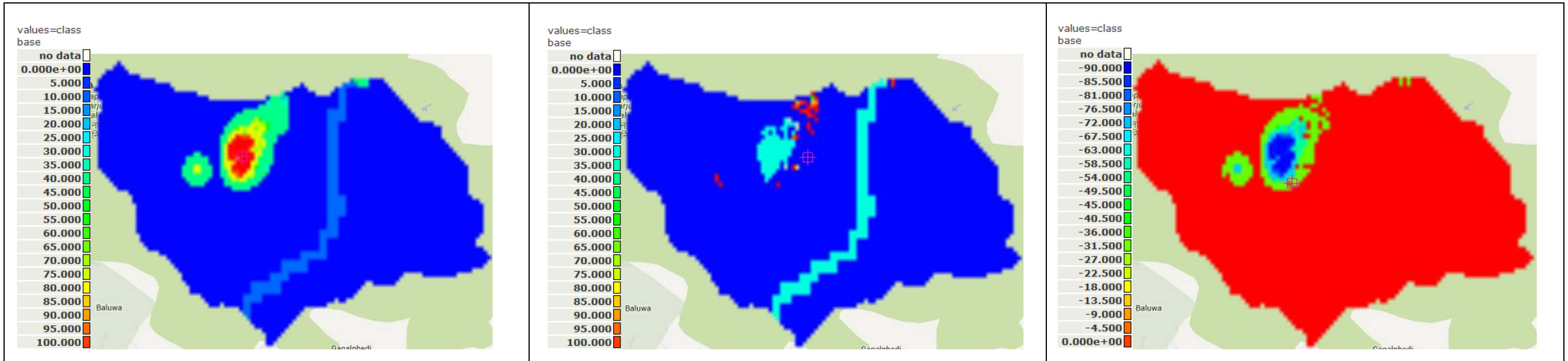
c. Baseline herb cover (mean: 41%)



d. Scenario herb cover (mean: 8.5%)



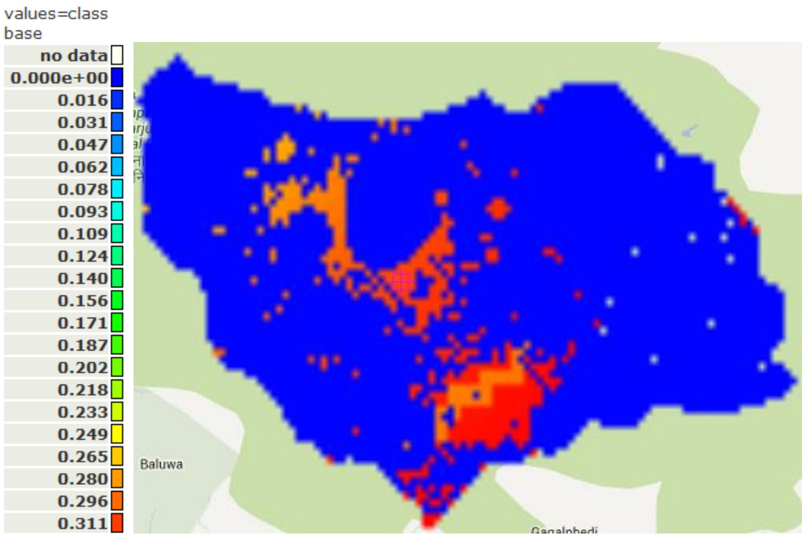
e. Differences (mean: -34%)



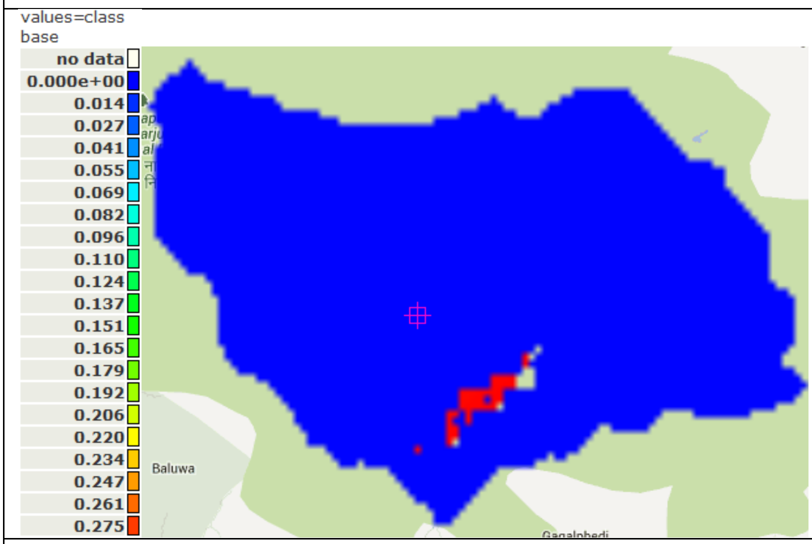
f. Baseline bare cover (mean: 4.6%)	g. Scenario bare cover (mean: 1%)	h. Differences (mean: 3.6%)

Figure 5-23: Change in percentage land cover between baseline and 'Scenario 2' land cover types

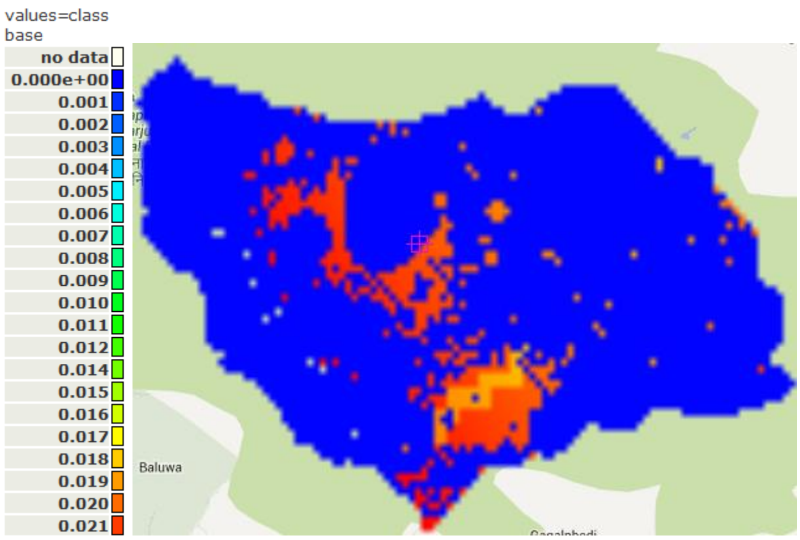
The scenario leads to an increase in catchment average tree cover percentage of about 37%, a decrease in herb cover percentage of 34% and a decrease in bare cover percentage of 3.6% (Fig 5.23, above). As a result, the overall catchment percentage tree cover becomes 90.5% while the herb and bare covers are decreased to 8.5% and 1%, respectively (Fig 5.23, above). The biggest increase in forest cover is seen in formerly human-dominated upland areas where cropland (herb) and bare land are the main land covers. Under this scenario, the cropland and pasture land also decreased substantially as the human settlements are to be relocated outside the catchment (see, Fig. 5.24, below).



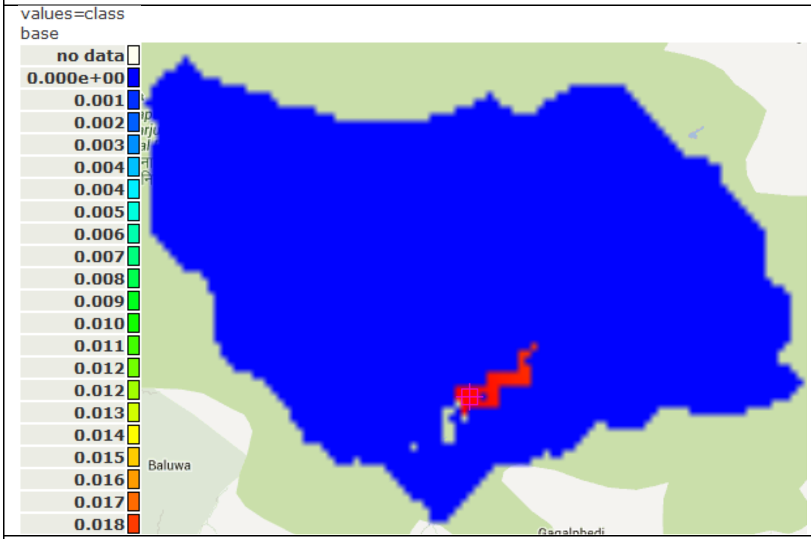
a. Baseline fractional cover of cropland (class: 0-1)



b. Scenario fractional cover of cropland (class: 0-1)



c. Baseline fractional cover of pasture land (class: 0-1)

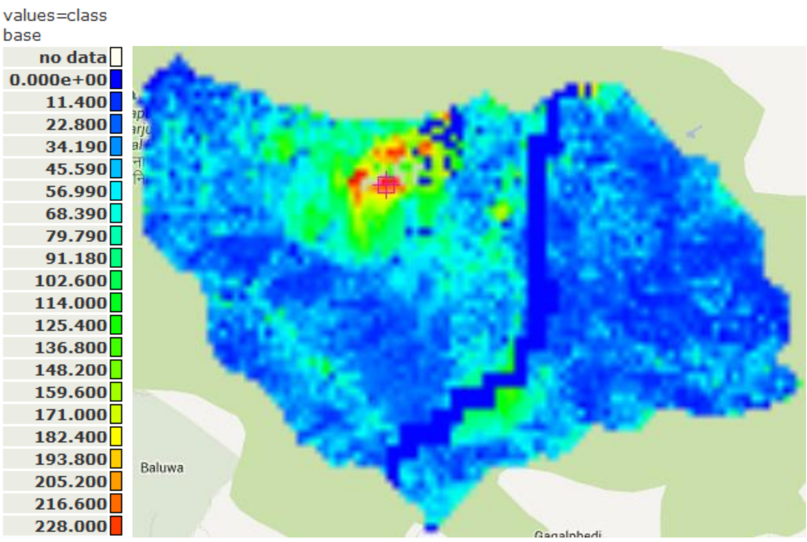


d. Scenario fractional cover of pasture land (class: 0-1)

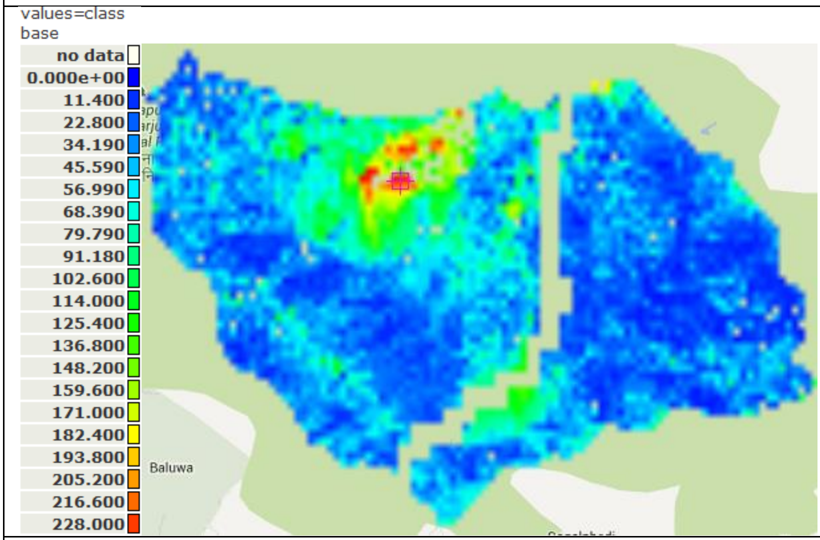
Figure 5-24: Change in cropland and pasture cover land under 'Scenario 2' land cover

The scenario leads to mean increase in AET for the sub-catchment of 41 mm/yr (15%) (Fig. 5.26, below) and mean increase in fog interception of 31 mm/yr (12%) (Fig. 5.27, below) leading to an overall mean decrease in water balance of 9 mm/yr (0.52%) (Fig. 5.28 below). Seasonally, monthly maximum AET for the area increases by 5 mm/month from 30 mm/month in August (baseline) to 35 mm/month in August ('Scenario 2'). Both evapotranspiration and fog interception processes are significantly increased in the areas of new forest growth which are largely occupied by cropland (herb) and human settlements in the baseline land cover. But, the opposing effects of evapotranspiration and fog interception on water balance mean that the overall impact is small with only a slight decline in water availability.

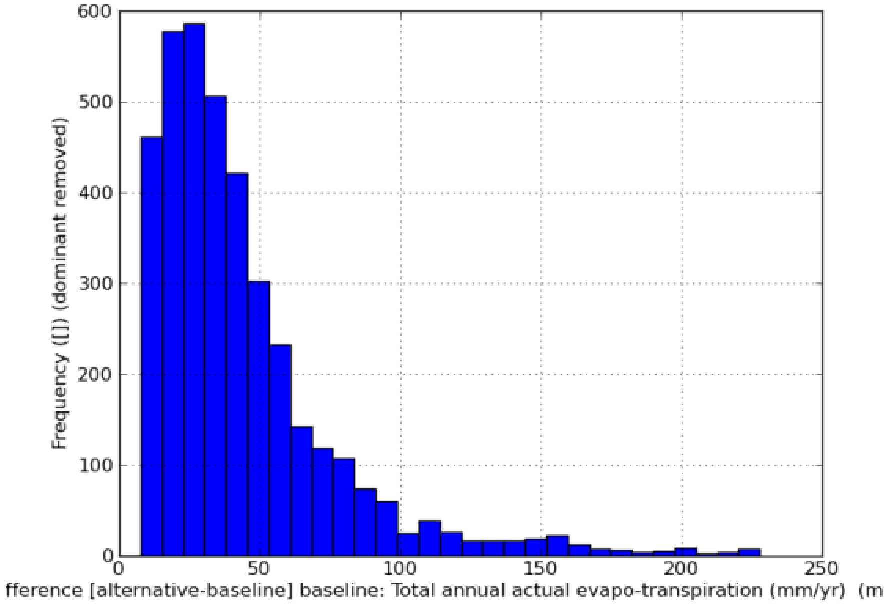
The AET increment would particularly occur in the areas where the reforestation activities would take place. The displacement of upland communities also provides additional reforestation opportunities in the catchment. The change in AET ranges between 0 and 228 mm/yr with percentage changes between 5% and 80% (Fig. 5.25, below).



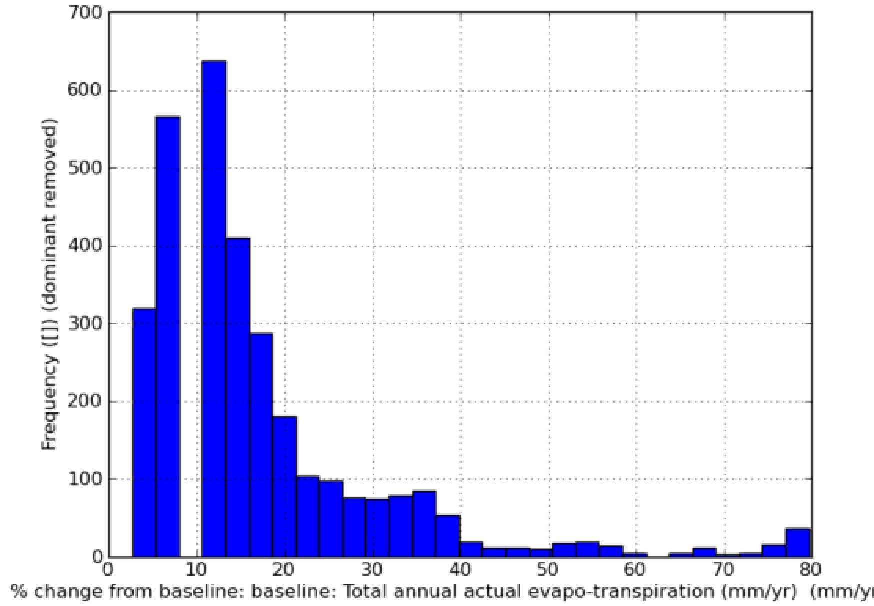
a. Actual change in AET (mm/yr) (mean: 41 mm/yr)



b. Pixels with positive change in AET (mm/yr)



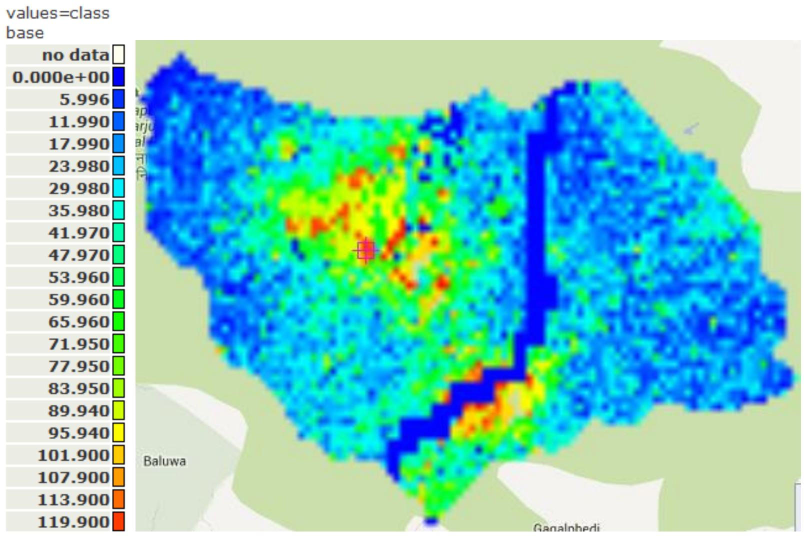
c. Frequency distribution of actual change in AET (mm/yr)



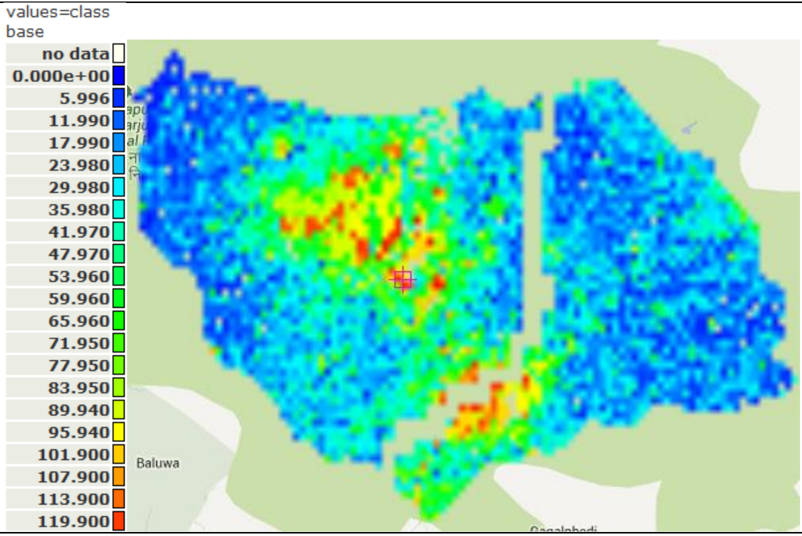
d. Frequency distribution of percentage change in AET

Figure 5-25: Quantitative change in annual AET ('Scenario 2' vs. baseline) (WaterWorld-V2, 2013)

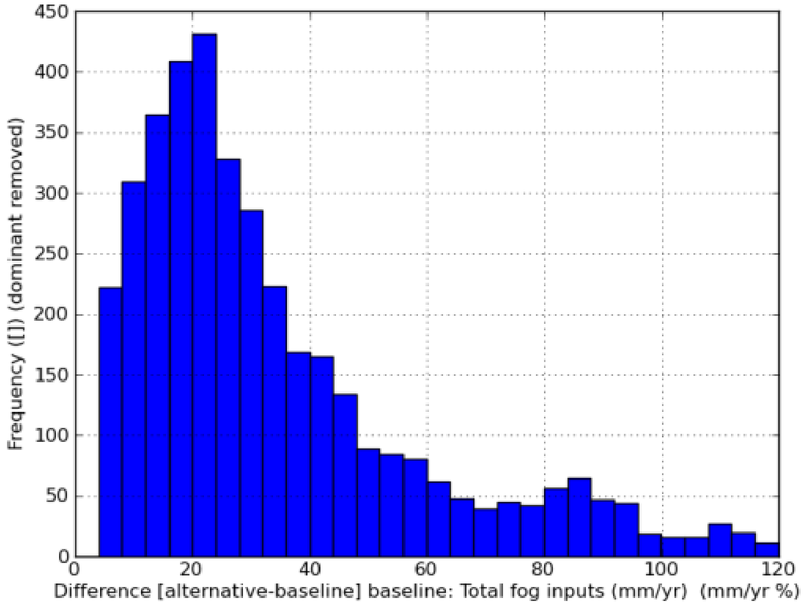
Once the forest cover is increased in the upland areas, due to suitable biophysical characteristics, the sub-catchment would also experience an increase in fog inputs. This will be concentrated in the higher mountainous region. The increment ranges between 0 and 119 mm/yr with percentage changes between 3 to 55%. As a result, the sub-catchment would witness an average 12% increase of fog inputs compared to baseline (Fig. 5.26, below)



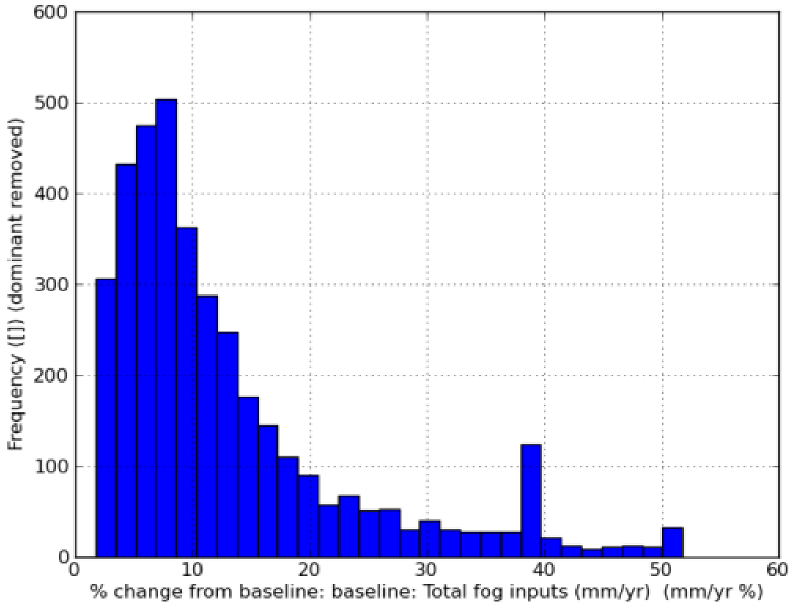
a. Actual change in fog inputs (mm/yr) (mean: 31mm/yr)



b. Pixels with positive change in Fog Inputs (mm/yr)



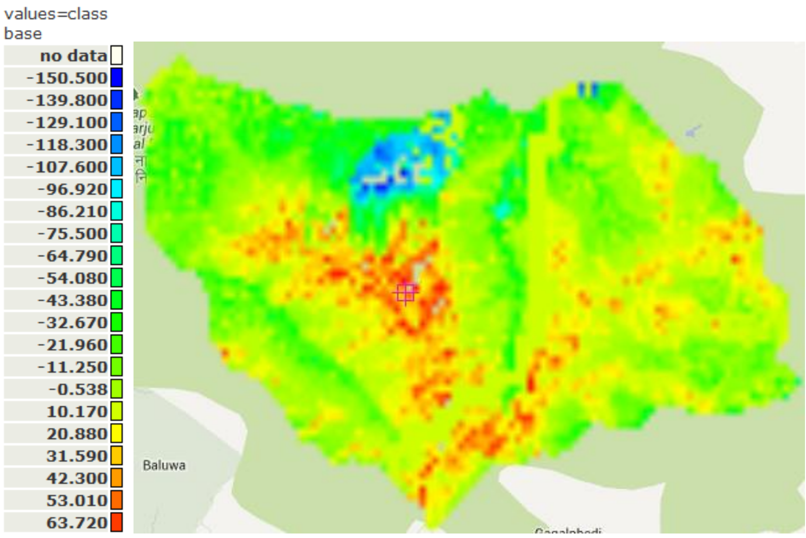
c. Frequency distribution of actual change in Fog Inputs (mm/yr)



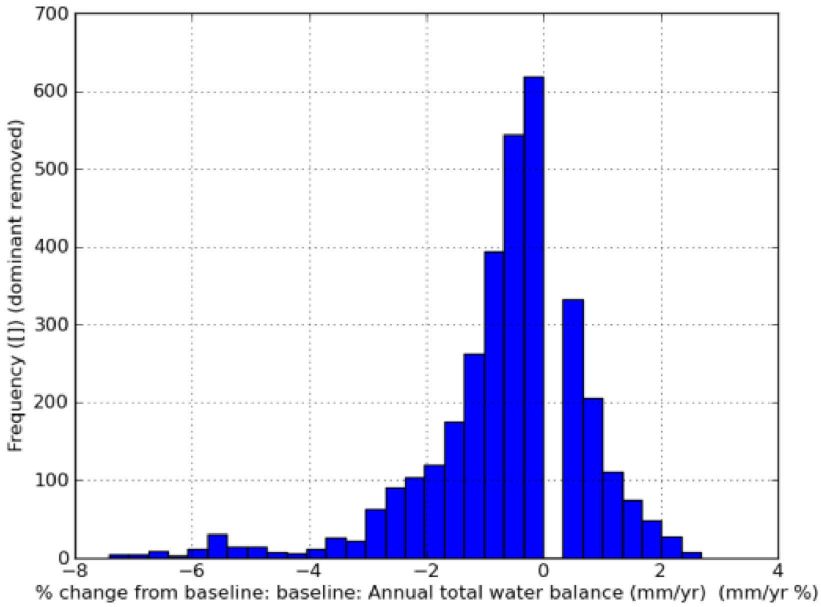
d. Frequency distribution of percentage change in Fog Inputs

Figure 5-26: Quantitative change in annual fog inputs ('Scenario 2' vs. baseline) (WaterWorld-V2, 2013)

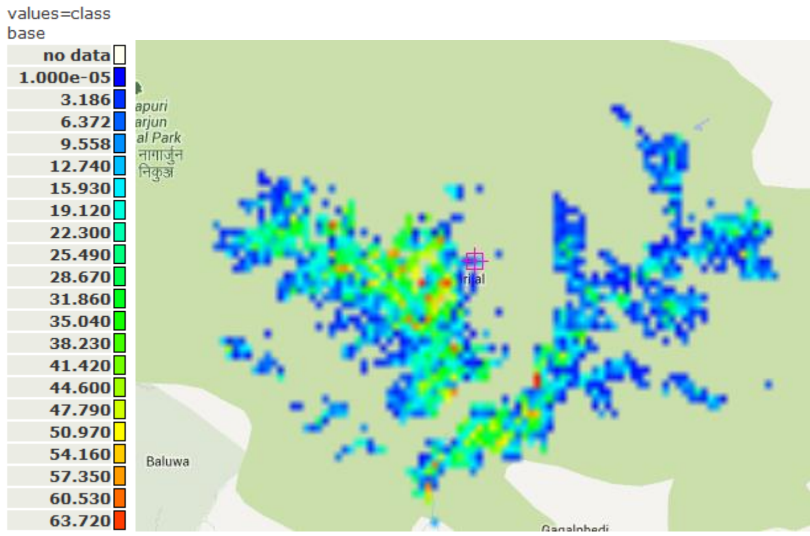
Under the 'Scenario 2', the sub-catchment would witness a marginal decrease in water availability which is largely because of relatively greater increase in AET compared to increased fog inputs. It also highlights the fact that the increased forest does not always enhance the water quantity for a catchment as is explained by Calder (2002). The change in water balance ranges between 150 mm/yr to 64 mm/yr with an average decrease of 9 mm/yr. This would diminish water availability by 354,000 m^3 annual. Parts of the sub-catchment would experience increased or decreased water balance depending on the change in input and output hydrological fluxes (Fig. 5.27 c&d).



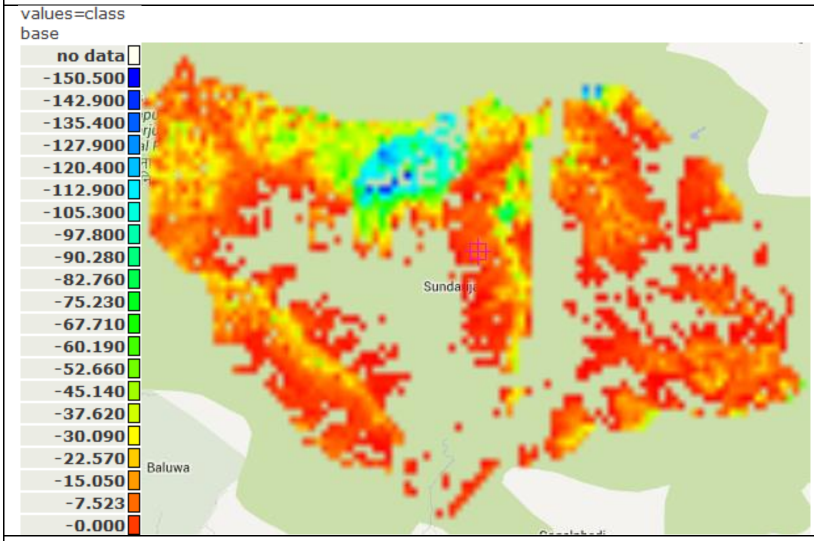
a. Actual change in water balance (mm/yr) (mean: -9 mm/yr)



b. Frequency distribution of percentage change in water balance



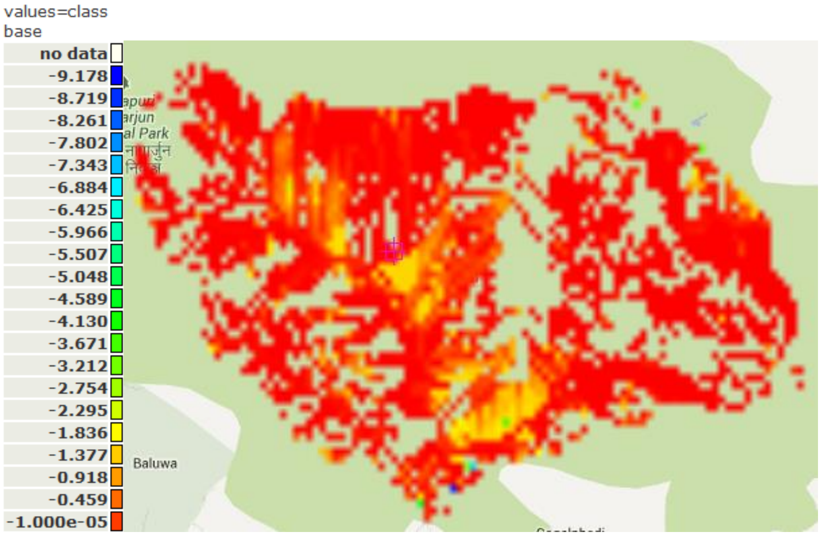
c. Pixels with positive change in water balance (mm/yr)



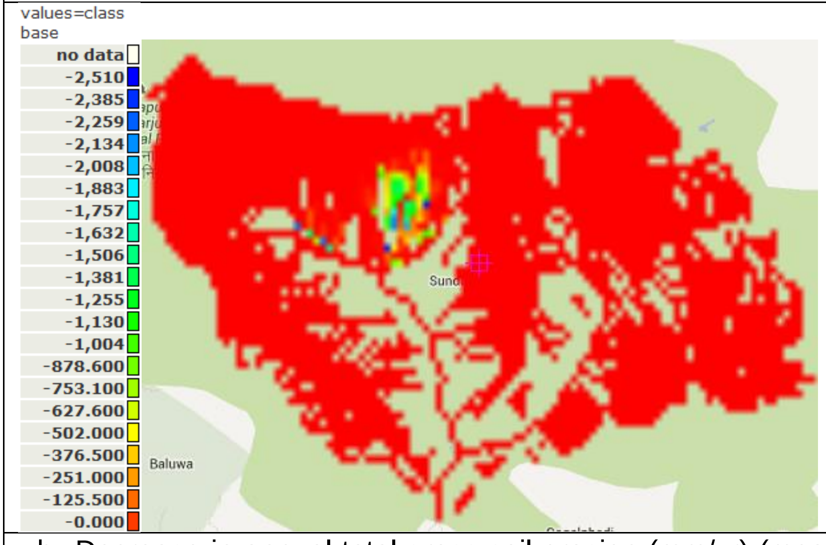
d. Pixels with negative change in water balance (mm/yr)

Figure 5-27: Quantitative change in annual water balance ('Scenario 2' vs. baseline) (WaterWorld-V2, 2013)

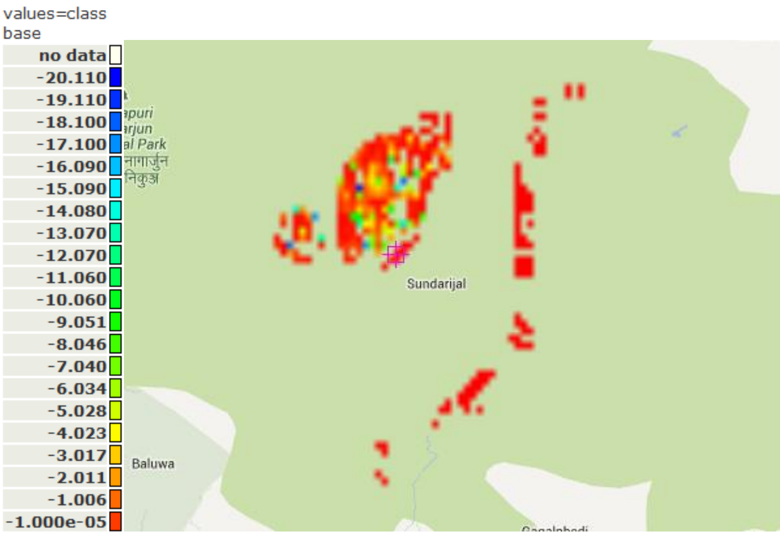
Under this scenario, the water quality related hydrological ESs including annual total gross soil erosion and human footprint have been improved to some extent (Fig. 5.28, below). The human footprint would decrease by 0.24% which is beneficial for better quality water locally and in the downstream areas. Replacing cropland and human settlement land use with a natural land use would also decrease in inputs of organic and inorganic non-point pollutants (fertilizers, herbicides, pesticides and manures), which would be expected to affect the water quality locally and downstream. Similarly, a decrease of 40 mm/yr in annual total gross soil erosion is also improving the hydrological regulatory ESs of the sub-catchment. Similarly, some parts of the sub-catchment will also witness decreased annual total hillslope net erosion (which is largely due to increased forest cover in herb and bare dominated areas). That will also benefit downstream beneficiaries as there would be less sedimentation process due to improved forest cover in the upland areas.



a. Decrease in human footprint on water quality (% contamination) (mean: -0.24%)



b. Decrease in annual total gross soil erosion (mm/yr) (mean: -40 mm/yr)



c. Decrease in annual total hillslope net soil erosion (mm/yr) (mean: -0.2 mm/yr)

Figure 5-28: Qualitative change in hydrological ES ('Scenario 2' vs. baseline) (WaterWorld-V2, 2013)

We have assessed the hydrological ESs of the Sundarijal sub-catchment using two different plausible LUCC scenarios. The study shows that there are some marginal differences in terms of gaining ESs benefits. Both scenarios offer some level of hydrological ESs benefits. Since the forest coverage is increased in both scenarios, the modelling findings show that there would be better regulatory services in either case. In terms of quantity related hydrological ESs, 'Scenario 1' (Integrated Watershed Management Approach) would generate an increased water availability while 'Scenario 2' (Human Resettlement and Reforestations) would result a negative water availability compared to baseline water balance (WaterWorld V2, 2013).

Both LUCC scenarios have shown positive impact on quality related hydrological ESs available for the downstream beneficiaries. The 'Scenario 2' which is based on human resettlement and extensive reforestation process has slightly lower level of human footprint on water. The availability of good quality water (with lower sediment and contaminant loading) would have a positive impact on human health, and lower costs for water treatment and distribution facilities.

The sub-catchment consists of two upland human settlements with a significant number of indigenous people who rely on agricultural based rural livelihoods. It would be a major challenge for PA authority to relocate upland people outside the catchment. In addition, the catchment is located at the close proximity of Kathmandu, so the overall cost of resettlement could be significantly higher compared to supporting upland communities to implement integrated watershed management programme. That would make real improvement in qualitative change of hydrological ESs. In this situation, PA authority could implement best suited watershed protection activities with an active participation of upland communities. Such initiative would benefit both local livelihoods and improve hydrological ESs.

5.4.5 Local perception on PA conservation and hydrological ESs

The study has carried out a household questionnaire survey as a qualitative assessment approach to assess local people's perception on water resources uses and watershed conservation. The survey has taken place in upland areas (Okharaini and Mulkharkha) and surrounding areas (buffer zones) between December 2011 and January 2012. Questions are focused on water sources and their management, availability (seasonal and annual), payment for water use, land use change and resulting impacts on watershed ESs. Respondents were also asked about the importance of PA conservation activities for various ESs benefits. Local people's perception on these various issues has provided valuable information about the hydrological ESs of the SNNP catchments.

Initially, we asked people about the available water sources and their management. Local people responded that springs, rivers and rainwater are the major water sources for their various uses. In term of water resources management, 43 respondents (86%) said upland communities manage resources themselves at the local level. The rest of the respondents said that a number of institutions including village development committees, district government, park authority and the KUKL are involved in water resources management. This shows the local communities' key role in water resources management in and around the catchments.

We also assessed people's perception of water uses at the local level. All participants said that they use available water resources for various purposes primarily domestic water consumption, irrigation and livestock management. Regarding water resources management, 45 respondents (87%) said that water resources are managed by measures such as building water infrastructures (including water tanks at sources and the installation of water pipelines), managing forests in the upstream areas and the protection of springs and wells by using fences. Local people also prioritized the supply of good quality water as the major hydrological ESs benefit available from the PA catchments.

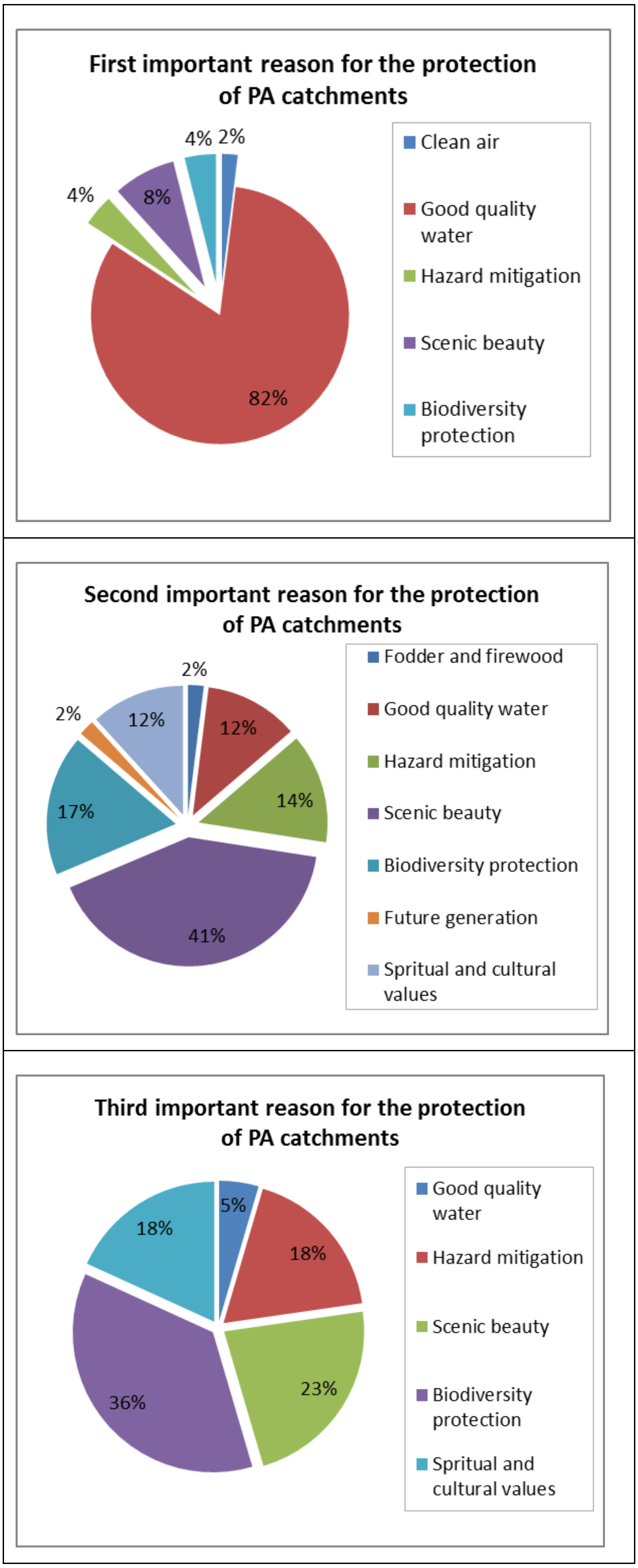


Figure 5-29: People’s perception about the protection of SNNP catchments

This study also tried to understand local people's perception about the reasons for the protection of SNNP catchments. The results shows that there is a clear view on the need for conservation of the SNNP catchments (Fig. 5.29, below). Out of 52 respondents, about 82% (43 respondents) believed that the most important reason for the protection is for a better quality of water supply. Similarly, about 8% believes that it is for scenic beauty to attract eco-tourism related benefits. People believing in hazard mitigation and biodiversity protection (including wildlife habitat protection) are about 4% each. And, the rest of the 2% also believe that the main reason for the SNNP catchments is for their capacity to provide clean air. Similarly, the second most important reason has been categorized as Scenic beauty (41%), biodiversity protection (17%), hazard mitigation (14%), good quality water (12%), spiritual and cultural values (12%), preserved for future generation (2%) and fodder and firewood (2%). Finally, the third important reason for the PA conservation is categorized as biodiversity conservation (36%), scenic beauty (23%), spiritual and cultural values (18%), hazard mitigation (18%) and good quality water (5%). Overall, local people said that the conservation programmes are designed for good quality water, scenic beauty (eco-tourism) and biodiversity conservation.

The above results show that the overwhelming majority of local people believe that the PA catchments are being protected for their capacity of supplying good quality of water. It indicates the important role played by the park in supplying better hydrological ESs to its actual beneficiaries. Then, there is also clear perception on other important ESs as local people prioritized the second and the third most important ESs as scenic beauty and biodiversity protection, respectively. This results also confirms that the interpreted capacity of SNNP catchment for providing valuable ESs.

5.4.6 Hydrological ESs and the prospect of a PES programme

Some past studies also emphasized that the SNNP catchments are supplying valuable freshwater ecosystem services to actual users in the downstream areas (Emerton and Iftikhar, 2006; Maskey, 2008 and Karn, 2008). However, there was a lack of quantitative and qualitative assessment of hydrological ESs change in different LUCC scenarios (based on plausible future conservation interventions). By estimating the magnitude of these changes at the water intake points for domestic water use and at the HEP dam, the research has shown that there is positive impact on water quantity and quality. Research findings would support the need for a PES scheme, so any integrated watershed management programme in the future will be more sustainable.

Moreover, a framework by which the PA authority imposes a ‘protection’ status could be failed without local participation, or ignoring their historical and moral rights to available local resources may negatively affect local livelihoods (van Noordjick, 2005). Opportunity costs for the resource exploitation by local people are also not addressed in policy and decision making processes. In SNNP, main beneficiaries such as water supply company and HEP authority could provide a share of benefits they gain from the use of better hydrological ESs to upland people. Such mechanism would also help to implement the integrated watershed management programme as this study also suggested a better option for the PA catchments.

5.5 Conclusions

The study concluded that the SNNP catchments are providing highly valuable hydrological ESs in the form of drinking water supply to Kathmandu valley and HEP generation to the whole country. This is confirmed by the park’s role in supplying about 58% of surface water and 46% of overall water resources (including surface and ground water) to the Kathmandu valley. Based on the size of the catchment and the downstream population, it is one of the world’s most highly valuable water ESs providers (Emerton and Iftikar, 2006 and Maskey, 2008). This shows the important role played by the catchments in supplying water to downstream consumers now and in the future.

Hydrological ESs modelling has improved the understanding of available hydrological fluxes and their distribution across the catchments. The catchment is producing better hydrological ESs in terms of quantity and quality (low sedimentation level) services. Due to lower human pressure, there is a low human footprint on water. Modelling results revealed that there is a significant level of fog contribution (an annual average of 11%) in annual water balance which is a significant development for the middle mountainous region of the Himalayas. However, there is still a lack of ground experiment confirming the level of CWI effect on total fog inputs. It is therefore, this study suggests for some ground based experiment for the better understanding of the true contribution of fog inputs in total annual water availability.

We also modelled hydrological ESs of a human dominated sub-catchment using two alternative LUCC scenarios. The first scenario was based on an integrated watershed management programme with local participation, and the second scenario was based on the relocation of human settlements and extensive reforestation in upland areas. Both scenarios have had positive influence on water services but in different scales. The first scenario has shown an increase in water quantity whereas the second scenario has shown the negative water balance (i.e. decreased water availability). In terms of water quality, both scenarios would have almost similar positive effect on sedimentation control, however in complete reforestation there will be less human footprint on water due to relocation of existing human settlements. Since the human resettlement could be costly and encountered with many socio-economic issues, integrated watershed management option would be better for the watershed conservation and maintaining better hydrological ESs.

People's perception on park conservation and various aspects of hydrological ESs has shown that the better conservation practices in the upland areas have resulted in an improved hydrological ESs to the vicinity and downstream beneficiaries. Upland communities highly value the hydrological ESs of the catchments and they believe that the conservation approach adopted by the SNNP authority is primarily focused for the safeguarding of the better quality of water supply. Since the upland communities including people living in the buffer zone areas are voluntarily contributing in better management of hydrological ESs, a set of integrated watershed management programmes (supported by the PES based mechanism) would further improve the hydrological ESs of the SNNP catchments in future.

Chapter 6 Assessing hydrological ecosystem services of the Kulekhani catchment - a human dominated mountainous region of the Himalayas

6.1 Background

In the previous chapter, we assessed the hydrological ESs of a Protected Area catchment. In this chapter, we must try to assess hydrological ESs produced by a human dominated catchment. The Kulekhani catchment is located in a densely populated mountainous region of Nepal. The area hosts the nation's only hydro-reservoir that has a crucial role in balancing energy supply to the country, especially during the dry seasons of the year. The reservoir (also refereed as 'Indra Sarobar') was created in 1982 by the construction of a 115 m high rock-filled dam at the outlet of the catchment. With an approximate size of 200 ha (about 1.7% of the catchment); the reservoir had an original water storage capacity of 85.3 million m^3. The reservoir supports two HEP stations (i.e. Kulekhani I and Kulekhani II), which collectively produce a total capacity of 92 MW. At the time of writing, the Kulekhani III (with a capacity of 14 MW) is under construction further downstream. This new HEP project is also designed to use water volume discharged from the Kulekhani II HEP station. The generated HEP from the stations is connected to the national grid and then distributed across the country. Therefore, the Kulekhani catchment is producing HEP related water provisioning services that benefits people far beyond its own catchment.

Available natural resources in the catchment are heavily exploited by local people to support their livelihoods. The population density of the watershed is traditionally high since it is located close to the capital city, Kathmandu. The majority of upland people are dependent on agriculturally based subsistence livelihoods, and there are limited jobs and livelihood opportunities outside the agricultural sector. Even poorly suitable mountain terraces have been converted to croplands to feed the increased population in the basin. The situation was further exacerbated by higher population growth in recent decades (CBS, 2012). As a result, the catchment experienced an unprecedented level of cropland expansion until the 1990s. Previously forested areas on the steep mountain slopes were gradually converted to sloping terraces, which became the most dominant form of land use (see, table 6.2 below). The vast scale of cropland development in the basin has changed the land use system and may have also affected the hydrological regime of the catchment.

Since the early 1980s, the catchment has witnessed a series of forest regeneration/afforestation activities (Pandeya, 2005). These activities were successfully implemented by government agencies in collaboration with upland people. Such programmes have had positive impacts on forest cover and agricultural practices. This may have played a direct role in supplying better hydrological fluxes, for example, improved annual runoff regimes, erosion control and reduced erosion and sedimentation.

The ability of a better-managed catchment to maintain water quantity and quality flow is one of the most tangible and valuable impacts on ecosystem services in the area. The land use system may have had a direct influence on the hydrological system and associated hydrological ESs. On the one hand, the upland rural communities only marginally benefit from the improved land cover. On the other hand, they are directly supporting water conservation through the implementation of conservation activities such as community forestry management and improved agricultural practices. These activities have downstream beneficiaries (notably the HEP companies) who are potentially profiting from the ESs provided by the better land use and land cover management in the upland areas. This study is trying to understand the magnitude of change in hydrological attributes i.e. quantity and quality (sedimentation load) produced by the Kulekhani catchment. Since the land use and cover change is directly controlled by the upland communities, the research has a profound policy implication in terms of how to sustain and/or improve hydrological ESs in the long-term.

6.2 Aim of this chapter

The aim of this chapter is to assess a major hydrological ESs (i.e. the HEP generation) produced by the Kulekhani catchment. To achieve the main objective set for this study, we have addressed a series of issues. First, we estimated the major surface hydrological fluxes such as annual wind driven rainfall, fog input, AET and water balance at the catchment scale. Secondly, the study evaluated human interventions, primarily watershed conservation activities and agricultural processes and their resulting impact on hydrological ESs. This was followed by modelling water quantity and quality attributes (sedimentation load and human footprint levels). We used a plausible forest growth scenario to investigate the likely impacts on hydrological ESs. Finally, the study also assessed the prospect of an existing PES based mechanism to maintain hydrological ESs. A better understanding of hydrological ESs produced by the Kulekhani catchment would generate new knowledge which could help design innovative conservation programmes for the mountainous areas.

6.3 The Kulekhani catchment – An introduction

6.3.1 Location and topographic features

The Kulekhani catchment is located in the middle-mountainous region of the Himalayas between Latitude ($27^0$34'N to $27^0$42'N) and Longitude ($85^0$01'E to $85^0$12'E) (Figure 6-1, below). The catchment encompasses an area of 125 km^2 and is situated 50 km south-west of its capital city, Kathmandu. The catchment contains different bio-physical and hydro-climatic zones with diverse landforms, climates, vegetation and socio-economic diversity. The altitudinal variation of the catchment ranges from a minimum of 1530 masl (at the highest level of the reservoir) to 2606 masl at the south western mountain peak (Figure 6-1, below).

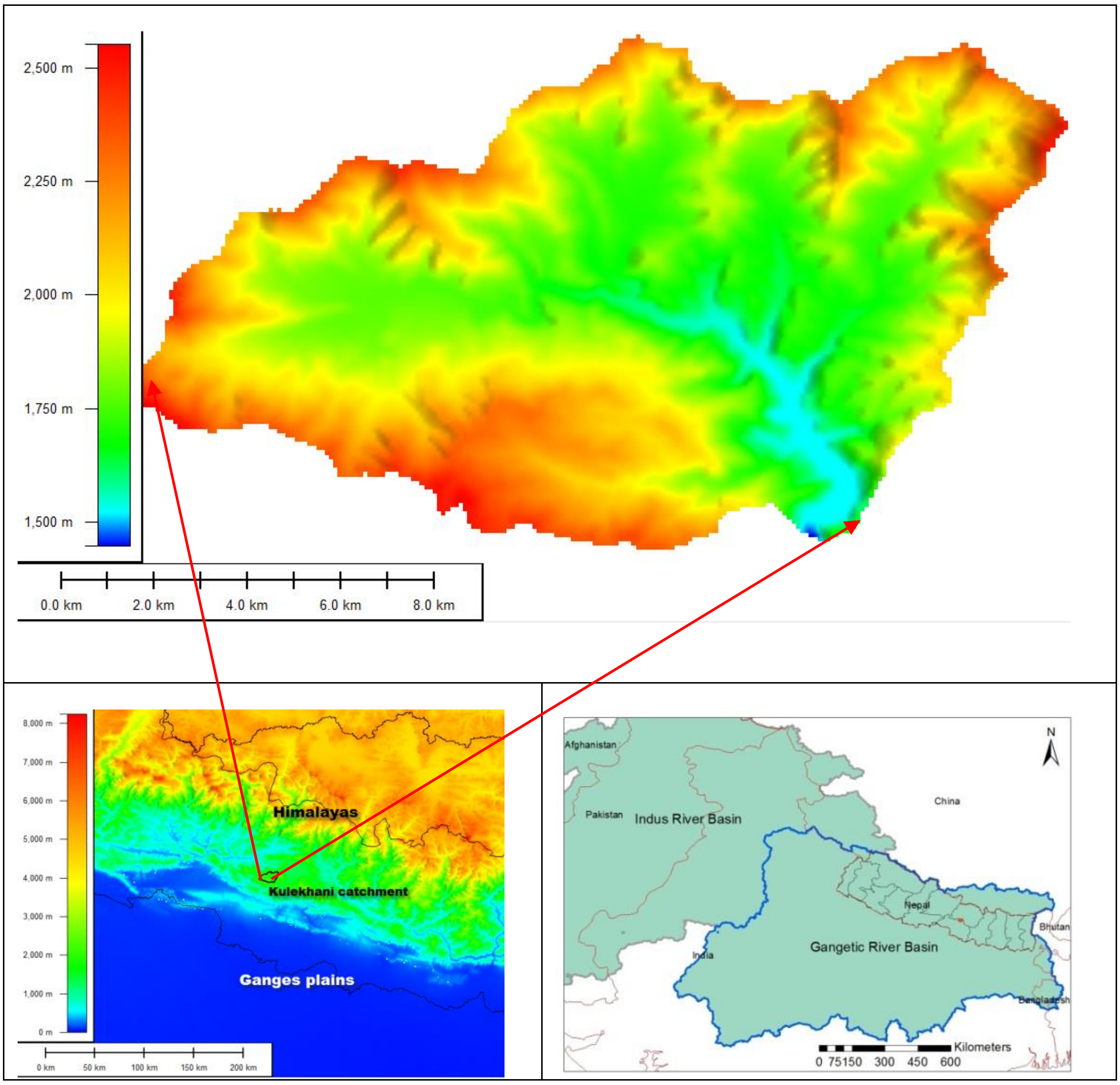
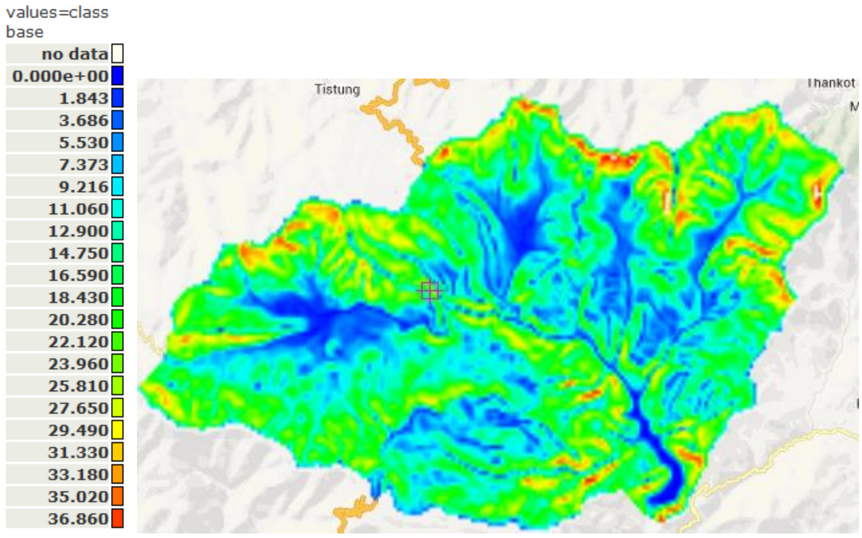
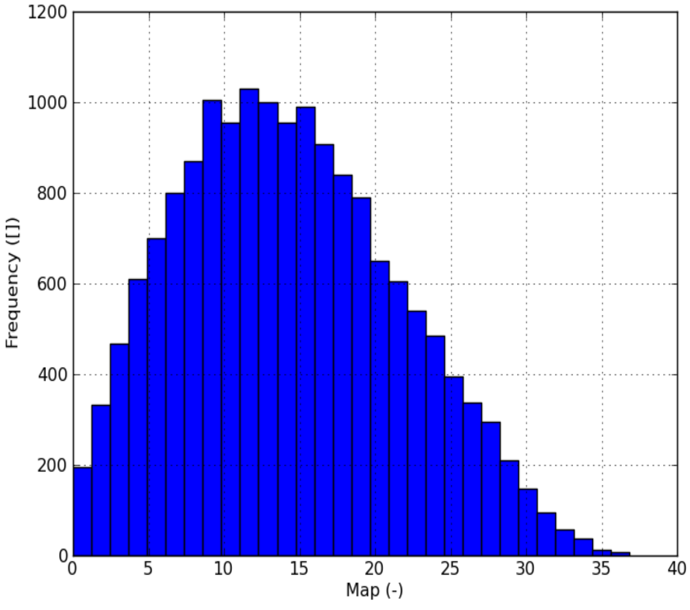


Figure 6-1: The location and elevation profile (SRTM HydroSHEDS) of Kulekhani catchment in the Himalayan region (Source; Lehner et al., 2008)

The catchment is made up of uneven terrain, hills and valleys. The mean elevation of the catchment is about 1930 masl. Using the 90m resolution HydroSHEDS DEM, we have derived a slope gradient map which has a range of between 0 and 37 degrees (Figure 6-2, below). The slope gradient map shows the highest slope gradient in the mountain ridges and the lowest slope gradient in the valleys. The frequency distribution of the slope gradient confirms that more than 90% of the landscape has a 30 degree or under slope gradient.



a. Slope gradient (degrees)



b. Frequency distribution of slope gradient (degrees)

Figure 6-2: Slope gradient and its frequency distribution (WaterWorld V2, 2013)

Topographic features have a direct influence on land management practices across the middle-mountainous region. Low to medium levels of slope gradients are suitable for the expansion of croplands and human settlements. Valleys and lowland areas with low slope gradients are used for intensive crop cultivation. Upland areas are mostly occupied by forest and natural vegetation.

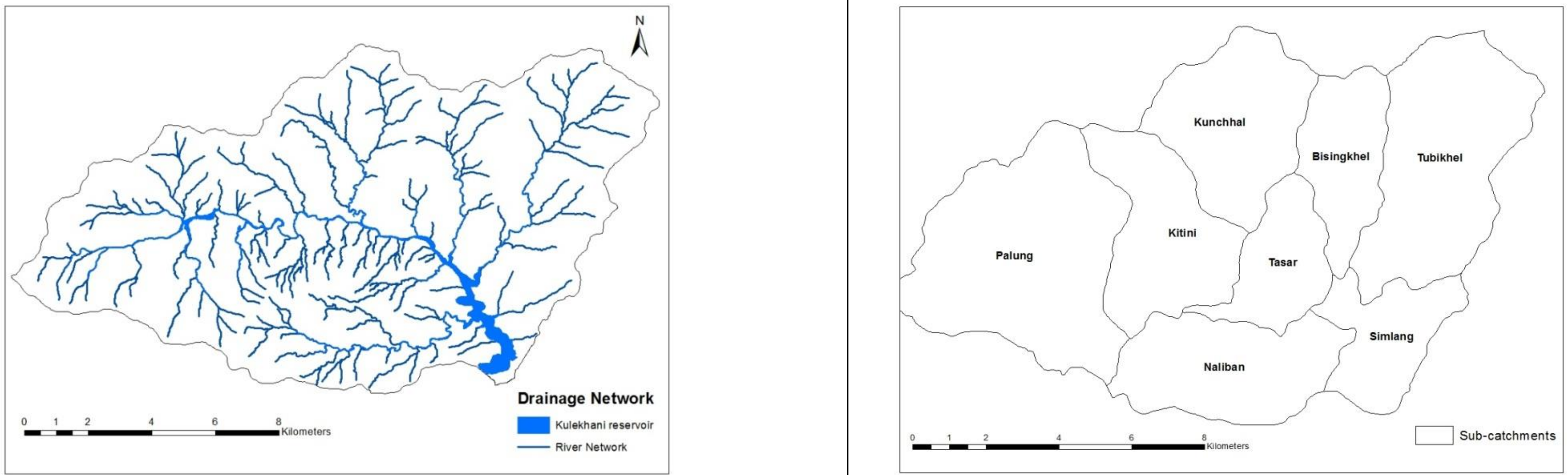
6.3.2 Climate, hydrology and drainage network

The catchment is under the influence of two major climatic zones, namely the warm temperate humid zone (between the altitudes of 1500 to 2000 masl) and the cool temperate humid zone above 2000 masl. Annual average precipitation is just above 1600 mm (DHM, 2011), most of which occurs during the monsoon season between June and September (Table 6-1, below). The table shows the average monthly rainfall for the three stations (Daman, Markhu and Thankot) between 1980 and 2010. On average, 77% of rainfall occurs during the monsoon (between June and September), 16% in early monsoon (April and May) and late monsoon (October), and 7% during the dry and winter periods (between November and March). The most important climatic factor for the region is the south-eastern monsoon as it determines the vegetation types as well as the possibilities for cultivation. In conjunction with the topography and water flow, vegetation is an indicator of the macro and micro climate in the watershed. It also play key role in the hydrological cycle at the watershed scale.

Table 6-1: Average rainfall received in the Kulekhani catchment (mm)

Location	Latitude	Longitude	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average total
Daman	27.60	85.08	2314	14.8	26.3	39.0	69.8	170.4	270.4	465.8	359.4	220.0	61.0	6.2	14.1	1717.4
Markhu Gaun	27.62	85.15	1530	19.3	26.7	34.9	65.1	132.5	220.0	363.1	282.3	201.0	40.9	8.8	20.2	1414.8
Thankot	27.68	85.20	1630	18.6	28.3	37.5	61.8	137.6	262.7	477.6	418.3	254.9	51.6	10.8	17.4	1777.0
Total mean				17.6	27.1	37.1	65.6	146.8	251.0	435.5	353.3	225.3	51.1	8.6	17.3	1636.4

Source: (DHM, 2011) [Note: Monthly records represent the average rainfall for 30 years from 1980 to 2010]



a. Drainage network

b. Major sub-catchments

Figure 6-3: An overview of drainage network and major sub-catchments of Kulekhani catchment (BIWMP, 2003)

The drainage network of the catchment shows the existence of a dense river network. The catchment is drained by the Palung River and several tributaries. The Palung River meets with the Gharti and Kitini tributaries on the right bank, and the Tistung and Bisenkhel tributaries on the left, before emptying into the reservoir (Fig 6.3a, above). The Kulekhani watershed can be divided into different 8 sub-watershed areas (BIWMP, 2003). These are: Palung, Kitini, Kunchhal, Bisenkhel, Tubikhel, Naliban, Tasar and Simlang. The major streams and tributaries of the Kulekhani River are the Palung Khola, Chitlang Khola, Kitini Khola, Tistung Khola, Tasar Khola and other small tributaries. Water flow coming from the tributaries is collected in the downstream reservoir for HEP generation.

6.3.3 Geology and land productivity

The catchment is composed of different geological features that include granite, quartzite, ancient alluvium, phyllite with marble bands, limestone, massive marbles and slates (BIWMP, 2001) (see, Fig. 6-4, below). Ancient alluviums are deposited in terraced form along the major tributaries which are deep in soil and thus good for crop cultivation. In the upland areas, the catchment is mostly occupied by granite (in the south-western mountainous areas) whereas quartzite and phyllite is found in the northern and eastern parts of the catchment. Such geological fragility influences the landslide and soil erosion across the middle-mountainous region (Gerrard, 1994). The productivity of valleys is relatively high and thus suitable for crop cultivation practices.

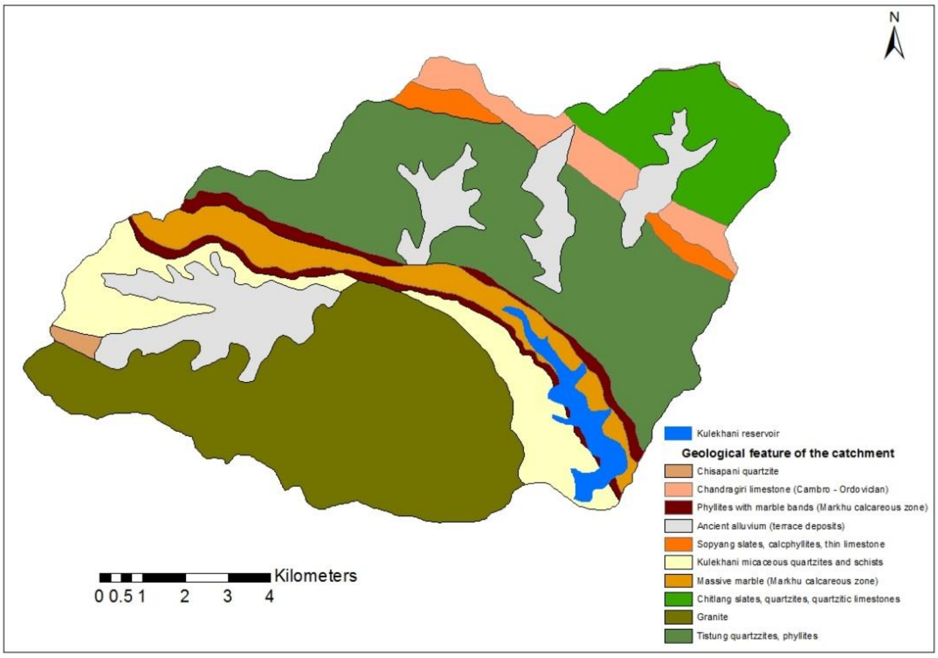


Figure 6-4: Geological profile of the catchment (LRMP, 1984)

Based on the slope gradient, depth of top soil and natural drainage systems, a land capability map was derived by the Integrated Watershed Management Programme (LRMP 1984). It is divided into five different classes (Figure 6-5, below). Class I and II (potentially the most productive land) is comprised of valleys and low lying foothills (between 0 and 5 degree slope gradient) which are well-drained and consist of deeper top soil. These areas are best suited for farming but require terracing and contouring for the best use of land. The Class III category of land is situated between 5 degree and 30 degree slope gradient, and is well drained and has a moderate thickness of soil. This land requires terracing in order to make it suitable for agricultural production. Category III land is also suitable for forest cover since soil depth is moderate. Class IV is located along the mountain ridges with the highest level of slope gradient (above 30 degree). This type of land has a low thickness of soil (<20 cm) and is not suitable for agriculture. However, it is suitable for forest cover. Class V consists of water bodies (reservoirs and wetlands) and some rocky sites. Although the above classes define the broader land capability, the land use system of the Kulekhani catchment is hugely influenced by human demand, such as the need for crop production, grazing land and infrastructural development.

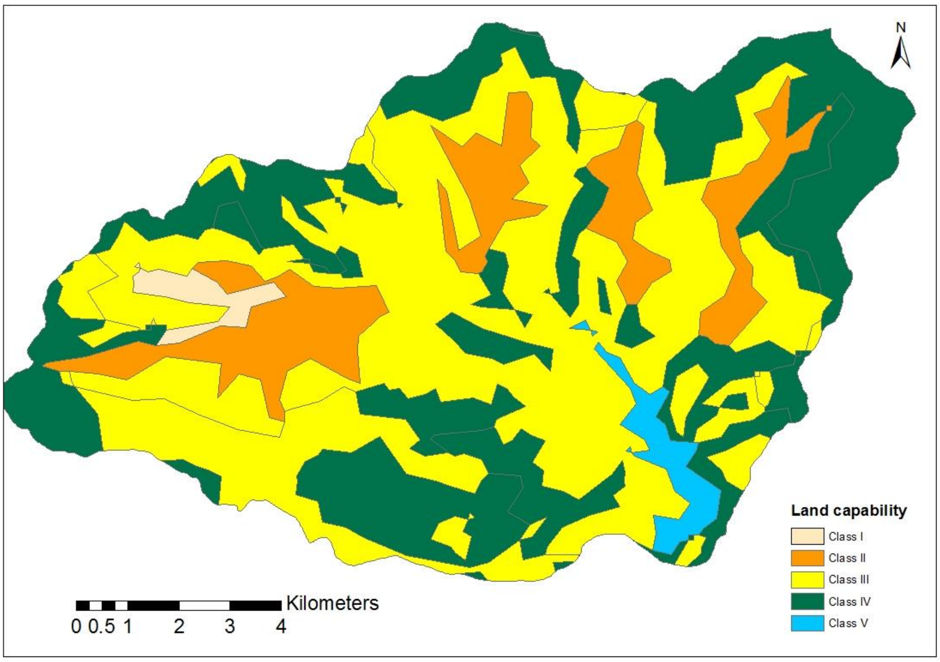


Figure 6-5: Land capability of the Kulekhani catchment (LRMP, 1984)

The areas that have a higher risk for soil erosion and sedimentation are also crucial for the better understanding of water quality related hydrological ESs. Erosion prone areas may produce large quantities of sediments which are eventually transported to the downstream reservoir by the catchment drainage network. Upland areas can be divided into low, medium and high risk areas for erosion and sedimentation. Generally, mountain croplands (especially upland slope terraces) have a higher risk of erosion and sedimentation. Exposure of bare land to rainfall makes the area more vulnerable for soil erosion. High erosion risk areas also include shrub land, river cliffs and barren areas. Forest covered areas are generally less prone to soil erosion, although such places are also vulnerable to sustained and high intensity rainfall. The alluvial plain areas with less than 5 degrees of slope gradient have a very low risk of soil erosion. Thus, the soil erosion and sedimentation processes are not only determined by the short and intensive monsoon rainfall but also by the existing land use and cover status.

6.3.4 Land use and cover types

Hydro-climatic and biophysical characteristics of the catchment always play a key role in the land use system. Soil characteristics, land productivity and water availability also have fundamental roles. Similarly, human interventions such as cropland expansion, conversation to pasture land and forest restoration have a direct impact on catchment hydrology (Potter, 1991 and Bruijnzeel et al., 2006). Different types of agricultural lands and cropping practices may have different levels of influences on hydrological balance. For example, paddy fields need a continuous water supply and thus may have a different set of hydrological influences compared to sloping agricultural terraces.

Land use and cover of the catchment is closely related to slope gradient. On the one hand, forest cover is predominantly found in the mountain slopes with a >10 degree slope. On the other hand, the croplands are concentrated in valleys and moderate slope areas. The Kulekhani catchment is mostly covered by forest and cropland (Fig. 6.6, below). Other major land cover types include wetland (hydro-reservoir), human settlements and the road network. Since the implementation of various watershed conservation activities, the land use and cover has been significantly changed. Forest patches dominate in upland areas, especially on steeper slopes. Cropland is distributed across the lowland areas.

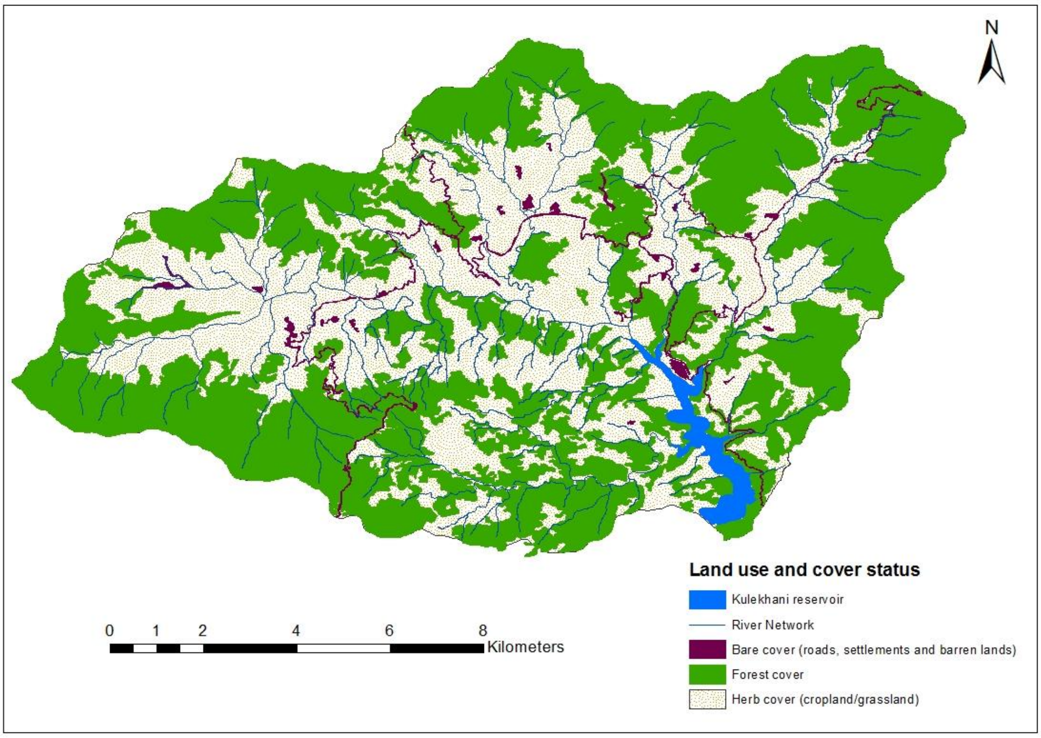


Figure 6-6: Present land use and cover types (Source: DigitalGlobe, 2013)

In such a human dominated area as the Kulekhani catchment, land use system is determined by human activities. Since the local people are dependent on croplands for their livelihoods, the suitable areas are converted into agricultural lands. Forest patches are concentrated in the upper-mountainous areas. In recent decades, the watershed conservation awareness supported by the government and NGOs has helped to improve forest cover across the catchment. As a result, the forest cover has been increased. The impact of such changes on the hydrological regime has to better integrate into hydrological ESs research. This would support watershed conservation and water resources policies in the long-term.

6.3.5 Demographic and socio-economic change

The Kulekhani catchment is one of the most densely populated mountain catchments in Nepal and is in close proximity to its capital city, Kathmandu. The catchment covers 8 Village Development Committees (VDCs) with more than 44,000 people (CBS, 2012). Human settlements are situated across the catchment, mostly in the valleys and lowland areas (Fig. 6.7, below).

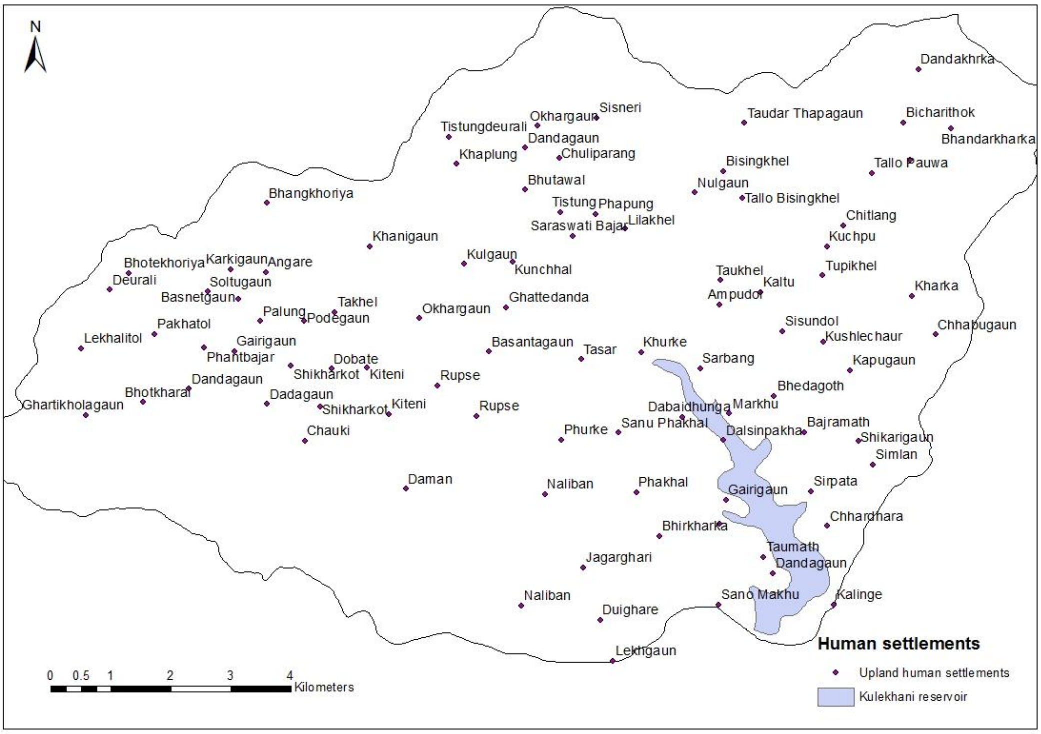


Figure 6-7: Major upland human settlements in the Kulekhani catchment (Source: BIWMP, 2003)

In the Kulekhani watershed, the population growth was very high during the 1981-1991 period, with additional residents increasing by 42%. Similarly, in the following decade, the watershed witnessed another big increase in population (10.8%). In contrast, the recent decade (between 2001 and 2011) has experienced negative growth (-4%) compared to the previous decade. The big increase in the 1980s and 1990s was directly related to higher birth rate in the watershed area. But, in recent decades, lower birth rate and higher emigration (for jobs and economic opportunities) may have contributed in decreasing the population ratio of the watershed (CBS, 2012).

Table 6-2: Population status of Kulekhani catchment area

Catchment VDCs	1981		1991		2001		2011	
	Total HH	**Population**	**Total HH**	**Population**	**Total HH**	**Population**	**Total HH**	**Population**
Bajrabarahi	--	--	1086	7132	1360	7427	1630	7675
Chitlang	1019	6292	1086	6417	1170	5830	1172	5029
Daman	1021	5551	1329	6898	1611	8360	1913	8439
Fakhel	638	3947	776	4491	906	4856	1011	4524
Kulekhani	717	4435	353	2960	591	3194	670	2969
Markhu	--	--	581	3126	661	3916	634	3071
Palung	784	4707	964	5243	1110	6029	1236	5603
Tistung Deurali	824	4388	990	5429	1190	6585	1405	7041
Total	5003	29320	7165	41696	8599	46197	9631	44351
Makwanpur District	40833	243411	56091	314599	71112	392604	86127	420477
Nepal	2585154	15022839	3328721	18491097	4253220	23151423	5427302	26494504

Source: (CBS, 2012 and BIWMP, 2003)

Note: VDC – Village Development Committee, HH – Household

1. In the 1971 Census Report, the population of above 8 VDCs was not clearly mentioned. Due to change in VDC boundary, the total population in the Kulekhani catchment region was 29320 (as per 1971 Census).
2. In the decade 1981-91, the annual population growth rate was 2.3% at national level, 2.9% at Makwanpur district level and 4.2% in the Kulekhani catchment area.
3. In the decade 1991-01, the annual population growth rate was 2.24% at national level, 2.4% at Makwanpur district level and 1.08% in the Kulekhani catchment area.
4. In the decade 2001-11, the annual population growth rate was 1.44% at national level, 0.7% at Makwanpur district level and -0.4% at the Kulekhani catchment area

Despite a small decrease in the overall population size between 2001 and 2011, the total number of households has increased by 12% in the same period, indicating smaller household sizes. Over the last three decades, the total number of households has increased by more than 90% (Table 6-2, above). The recent decline in population could be due to absentees of certain groups, especially youths and those who are unemployed and so have migrated for jobs, better education and livelihood opportunities. Ethnically, the catchment has become very diverse. In 2001, there were more than 26 different ethnic communities in the catchment (Pandeya, 2005).

The catchment provides various ecosystem services such as freshwater, crops and forest products to local people. Cropland is a major natural resource base that provides agricultural base ESs. Water supply is an essential natural resource that supports many aspects of local livelihoods such as crop production, fisheries and domestic water provisioning services. Local people also use forest resources extensively for fuel wood, fodder, timber and non-timber forest products (NTFPs). Recently, the fishery industry has grown due to the creation of the hydropower reservoir. Nature based eco-tourism ESs are also increasing since the development of infrastructures such as road networks and hotel businesses. Thus, the catchment is a rich source of various ESs that are directly beneficial to local people.

6.4 A review of past conservation interventions

Considering the vital role of the Kulekhani reservoir in supplying hydro-electricity, the Department of Soil Conservation and Watershed Management (DSCWM) started their Soil Conservation and Watershed Management (SCWM) programmes from 1978 in order to increase the watershed vegetation cover to reduce sedimentation/siltation in the Kulekhani reservoir and thus increase the life span of the HEP project (Voutilainen, 1993). The conservation programmes were aimed at enhancing the afforestation/reforestation activities across the watershed. Various SCWM programmes were implemented with the financial and technical assistance of the government, the HEP authority and various international agencies. The catchment has experienced a range of conservation related activities such as conservation plantations, silvi-pastoral improvement, conservation ponds, water source protection such as fencing springs and wells, terrace maintenance and improvement, gully treatment using bioengineering methods, road slope stabilization, trail improvement to control soil erosion, maintenance of irrigation channels and river/stream embankment protection. Major SCWM programmes in the catchment are listed below (BIWMP, 2001).

1) Resource Conservation and Utilization Project (RCUP) (1978-1982):
   The conservation project was implemented with the support of HMGN and USAID. The project had established plant nurseries and started conservation plantation in some parts of the degraded areas in Chitlang and Markhu regions (fig 6.8 below). Technical assistance had been provided in order to continue the SCWM programmes.
2) Kulekhani Watershed Management and Conservation Education Project (KWMCEP) (1982-1986):
   This project was implemented in the Chitlang, Markhu and Kulekhani areas (fig 6.8, below) with the support of HMGN and UNDP/FAO. SCWM

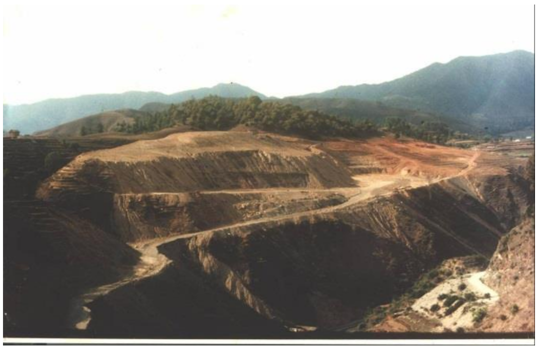
programmes were focused on erosion control measures in hot spot areas such as gullies, landslides, road slopes, outward sloping terraces and the burrow pit area (a main site from where clay soil was transported to line the rock filled dam). A combination of conservation activities such as the construction of check dams and run-off diversion channels, bio-engineering measures and tree plantation activities were implemented. In addition to these activities, various preventative measures were also implemented across the catchment in order to improve soil and water related services. These activities included conservation farming, upland terrace improvement, fruit tree plantation, community orchard development, fodder tree and grass plantation, foot trail improvement, drinking water spring protection, water supply and irrigation canal improvement and the construction/improvement of conservation ponds.

The participation of the locals was crucial to the successful implementation as well as the sustainability of project activities. The project had also focused on conservation education to raise awareness about the potential benefits of soil conservation and watershed management activities. The project trained local communities in enhancing their capabilities for the sustainability of project activities. In addition, such activities helped to improve the productivity of land and water resources in order to raise local incomes and improve livelihoods (BIWMP, 2001).

3) Watershed Management Project (WMP) and Kulekhani Watershed Soil Conservation Project (KWSCP) (1987-1994)

This conservation project was supported by FINNIDA and extended to many parts of the catchment, including the Bajrabarahi, Tistung, Palung and Daman areas. Demand driven activities such as land use planning, natural disaster prevention measures, land productivity and rural infrastructure protection programmes were also supported to address the needs of local people.

The project primarily concentrated on implementing bioengineering works and erosion control measures. The project was also focused on local empowerment through capacity building programmes, developing community ownership over local resources, establishing community-based organizations and women’s development activities. Projects had significantly contributed towards the expansion of community forestry activities in the region. During the project period, most forest lands were handed to the community forestry user groups (CFUGs). Technical support was also provided for the identification of potential community forests and handing over management to local communities. Projects had also supported local NGOs such as youth clubs and mothers' groups to develop their capacity in implementing their social development activities in the region. Various income generation activities were also initiated such as fruit tree plantation, goat keeping and mushroom cultivation. The success of the SCWM activities can be clearly seen in the areas where watershed conservation activities have taken place. These areas show the successful regeneration of conservation plantations in the borrow pit area and one of the reforested areas (Figure 6.8, below).



a. Borrow Pit Sarbang Area Before Implementation of Treatment Measures in 1982

b. Borrow Pit Sarbang Area after Implementation of Treatment Measures In 1988

c. Biruwa Ban Conservation Plantation site in Chitlang in 1983

d. Biruwa Ban Conservation Plantation site in Chitlang in 2003

Figure 6-8: A glimpse of conservation interventions at degraded lands (Source: BIWMP, 2003)

4) Bagmati Integrated Watershed Management Programme (BIWMP) (1997-2003):

After the completion of the FINNIDA supported Watershed Soil Conservation Project in 1994, the DSCWM had continued the SCWM programmes with support from the government. In 1997, the BIWMP (phase I) was introduced with the primary aim of maintaining and supervising the SCWM programmes. In 1998, the BIWMP (phase II) implemented multi-disciplinary and integrated approaches with ‘Poverty alleviation and environmental conservation’ goals (BIWMP, 2001). The project aimed to achieve the following; improved institutional capacity to manage catchment resources, improved conservation awareness, reclaimed degraded land, improved community management and better utilization of natural resources, promoting income generation opportunities and improving infrastructure for accessibility. The project was completed in 2003 with some major successes in catchment conservation such as transferring 5,350 ha to community forestry, establishing 70 CFUGs, creating 9,568 members, 1,436 training placements and 565 households with new CF based income generating activities (BIWMP, 2003).

A wide range of watershed protection measures were also implemented across the catchment to control soil erosion and improve local livelihoods (Figure 6.9, below). They included bio-engineering based slope stabilization activities such as landslide treatment, gully treatment, foot trail improvement, torrent control measures and irrigation system improvements. Similarly, a variety of agricultural land improvement activities were supported such as fruit & fodder plantations, demonstration plots, promoting agroforestry system, forage enrichment in marginal land, on farm conservation and sloping agricultural land technology (SALT).

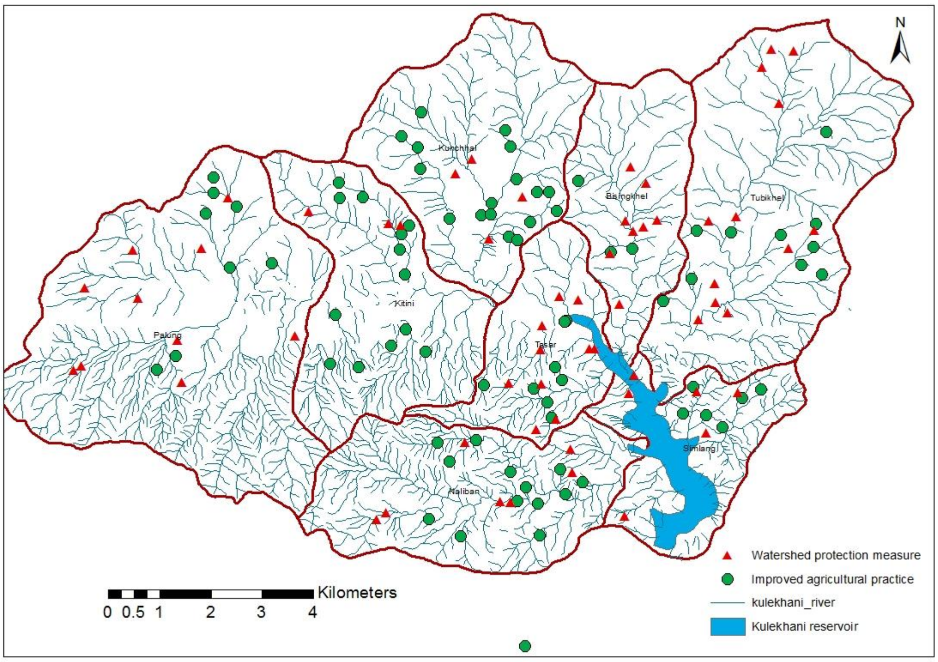


Figure 6-9: Watershed protection measures implemented between 1998 and 2003 in the Kulekhani catchment (BIWMP, 2003)

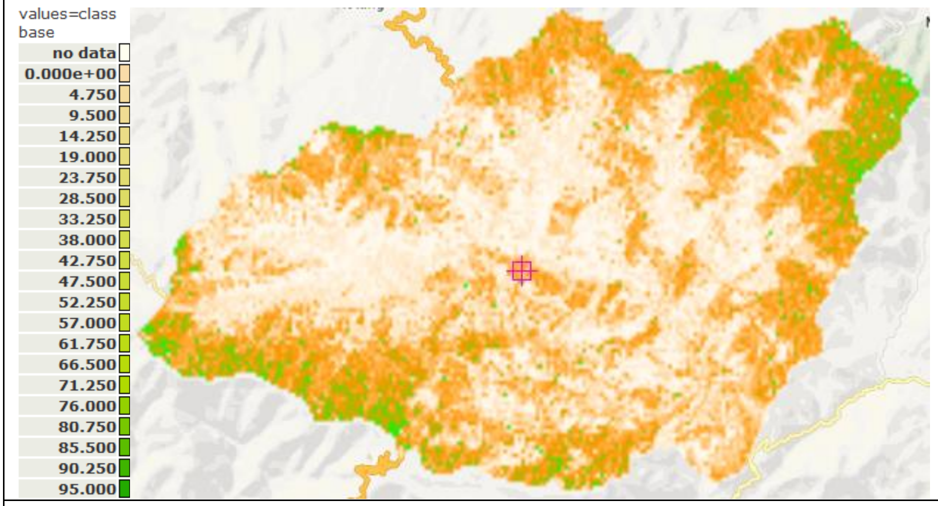
Upland communities played a central role in the implementation of watershed management programmes. Coinciding with various watershed conservation activities, the region also witnessed a major paradigm change in forest protection as most of the forest areas were handed over to local communities for better management. As a result, more than 90% of total forest cover is now under community forestry management (DHM, 2011).

Since the completion of the BIWMP II project in 2003, the external support for watershed management has been interrupted. Between 2003 and 2007, ICRAF (International Centre for Research in Agroforestry) and Winrock International led a research based project to assess the role of upland communities in watershed management. After realising the key role played by the upland residents in conservation efforts, a PES project has been implemented since 2005 to reward those communities in such a way that ES provisions will be maintained appropriately (Upadhyaya, 2007 and Pandeya, 2007). The details of the PES programme are explained in section 6.6.7 below.

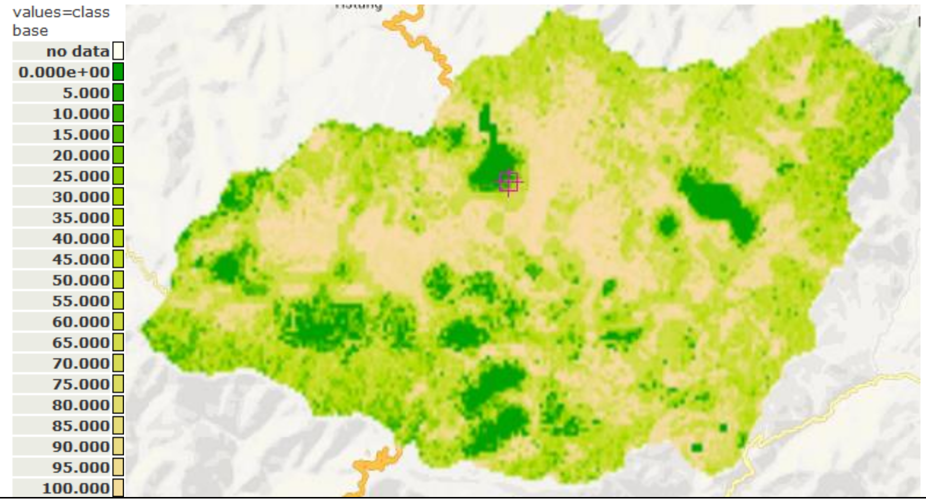
6.5 Results and discussion

6.5.1 Quantifying hydrological ESs

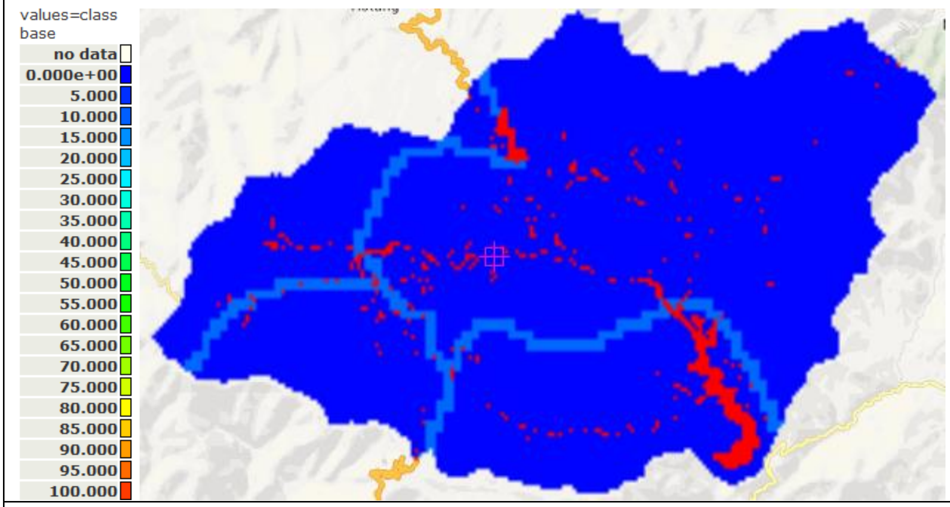
Initially, we have quantified the baseline hydrological fluxes. Using the 'SimTerra' database, the study has developed major land cover types. The overall landscape is dominated by tree cover (31%), herb cover (55%) and about 4% is covered by human settlements, road networks and reservoir and built up areas (Fig. 6.10, below). Since the water body is a non-vegetated area, the reservoir is also considered as a bare cover area in this study. Both tree and herb cover areas have been derived from the Landsat land cover circa 2000 – 2005 (Sexton et al., 2013). Tree covered areas are located in the upland areas while the herb cover (that mostly constitute croplands) are concentrated along the valleys and lower slope areas.



a. Tree cover (mean: 31.3%)



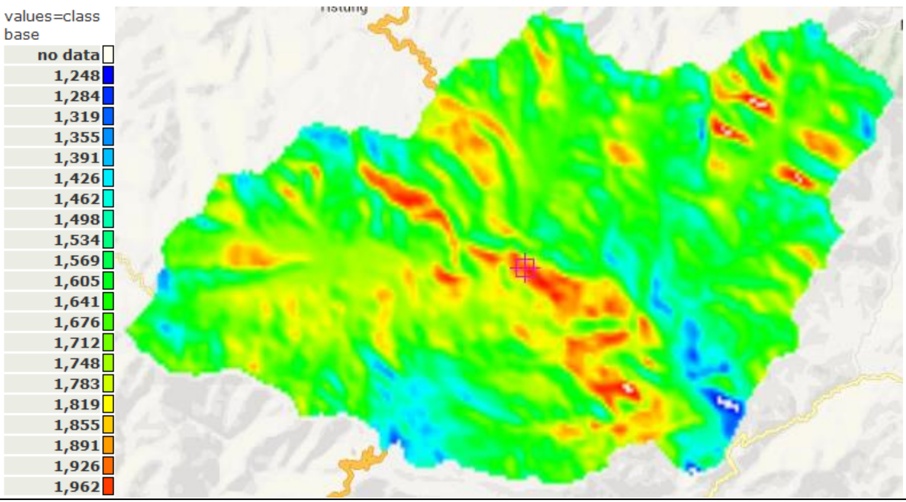
b. Herb cover (mean: 55%)



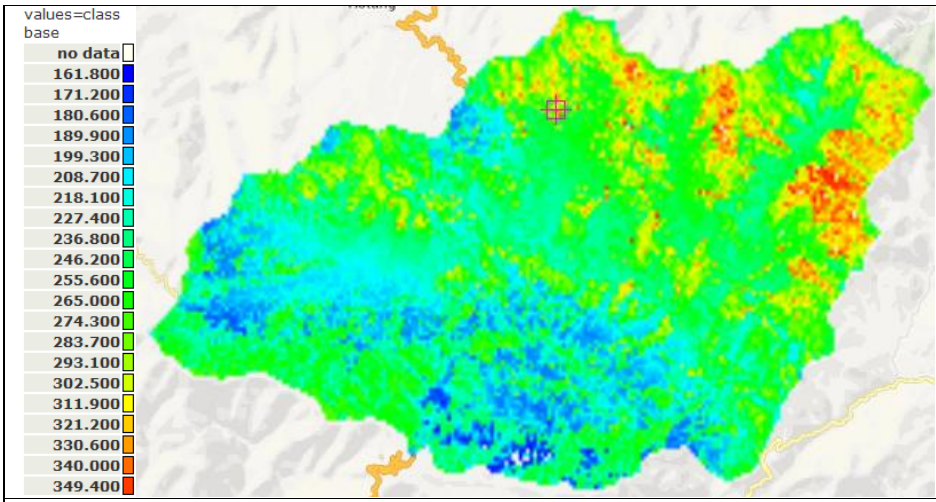
c. Bare cover (mean: 4.2%)

Figure 6-10: Landsat land cover map representing tree, herb and bare cover (Sexton et al., 2013)

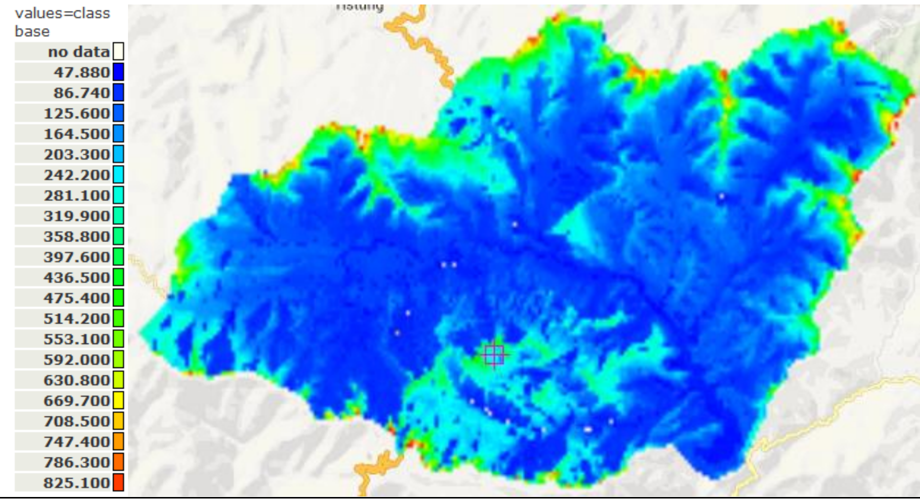
Using available hydro-climatic and biophysical datasets from the SimTerra database, the study first estimated annual hydrological fluxes such as rainfall (wind corrected), actual evapotranspiration (AET), total fog inputs and water balance (Figure 6.11, below). It went on to use mean monthly rainfall records of three ground stations (located within and around the catchment) for the past 30 years of period between 1980 and 2010 (see, Table 6.1, above). The modelling results show that the catchment receives an average of 1640 mm/yr wind-driven rainfall and an average 245 mm/yr of total fog input (Fig, 6.11, below). The fog input is higher in the north-eastern part of the catchment where high mountain areas and dense forest cover have supported the higher fog input (up to 350 mm/yr). Total annual AET in the catchment ranges from 48 mm/yr to 825 mm/yr with an average of 166 mm/yr. It is high in forested areas which are concentrated along the mountain ridges. Finally, the annual average water balance is about 1720 mm/yr, which is the amount of water available after AET. It is relatively high in valleys and lowland areas where AET is lower, as those areas have less vegetation cover compared to tree cover in the upper catchment.



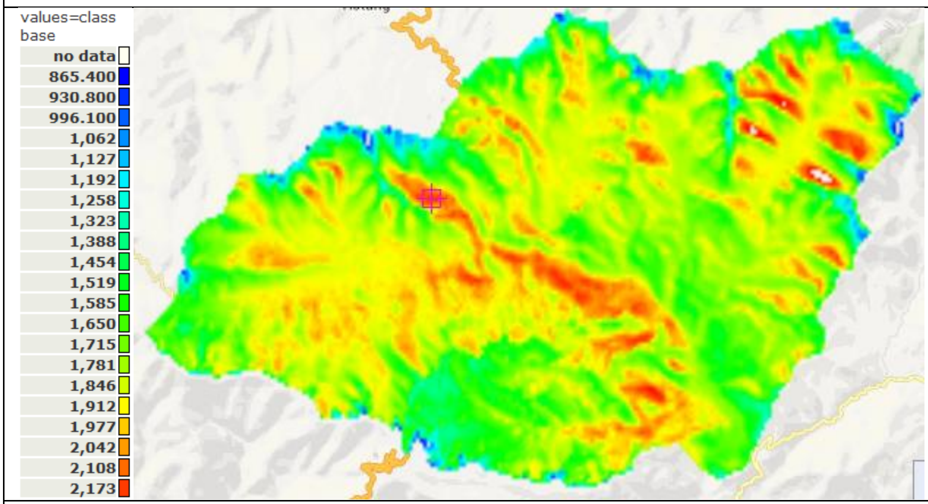
a) wind driven rainfall (mean: 1640 mm/yr)



b) Total fog input (mean: 245 mm/yr)



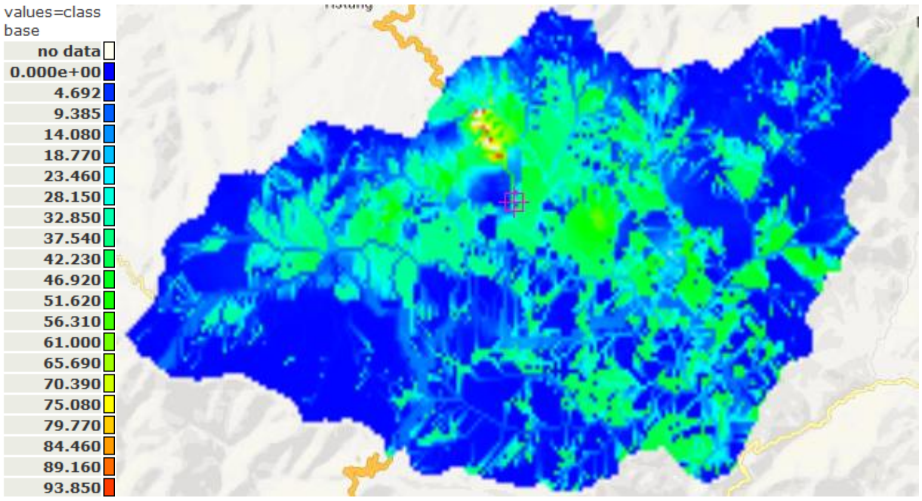
c) Actual evapotranspiration (mean: 166 mm/yr)



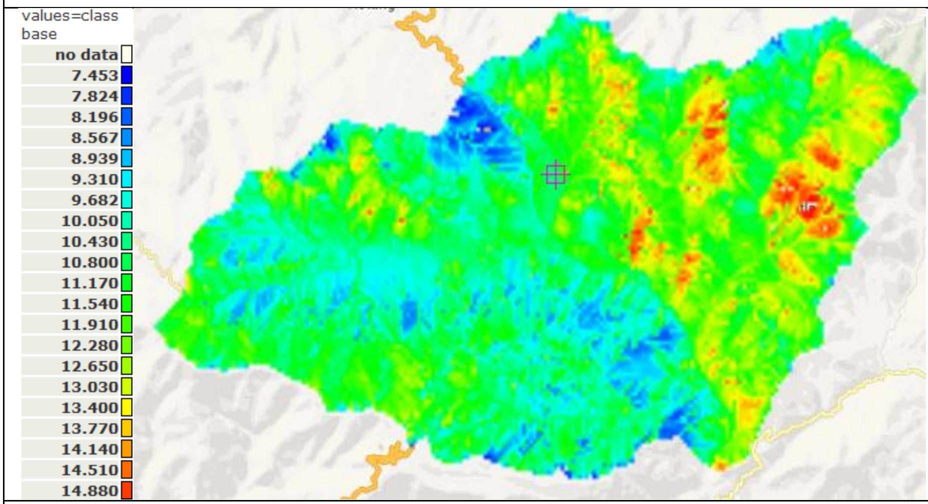
d) Water balance (mean: 1720 mm/yr)

Figure 6-11: Annual water budget at Kulekhani catchment area (mm/yr) (WaterWorld-V2 2013)

The annual water balance is the surplus hydrological flux (after the annual AET processes) which flows downstream as runoff, throughflow or baseflow, thus becoming available for the hydro reservoir. Therefore, a higher water balance may lead to improved hydrological services for the downstream HEP project. Since the summer monsoon contributes more than 80% of total annual rainfall, the available water fluxes (in the form of runoff, infiltration and aquifer storage) are accordingly high in that period. The catchment's hydro-climatic suitability for the CWI effect also significantly contributed in annual water balance although its exact role needs to be examined using ground based fog input experiments.



a. Human footprint (% contamination) (mean: 15%)



b. Annual % runoff generated by fog inputs (mean: 11%)

Figure 6-12: Hydrological quality/regulatory related ESs of the Kulekhani catchment (WaterWorld V2, 2013)

Quality related hydrological ESs show that better services are being delivered by the forest covered areas in the uplands (Fig. 6.12, above). The average human footprint of the catchment is about 15% but it ranges from 0 to 94%. There is a very low human footprint in forest dominated areas but it is very high in the human settlement areas. Similarly, the catchment's fog generated runoff has a mean of 11% which is a key hydrological ESs. Thus, the modelling results confirm that the catchment is supplying improved hydrological ESs to downstream beneficiaries.

6.5.2 Conservation impact on land use change

We have assessed past conservation activities and their impact on land use and cover change in order to understand the historical changes in the land use system. This has helped to develop future plausible land cover scenarios. During the time of rapid population growth (from the middle to the end of the 20th century), the catchment witnessed an unprecedented level of cropland expansion. Available lowland areas and most of the mountain terraces were converted to cropland to support the growing population. As a result, the herb cover was the dominant land cover type in the 1990s.

From the early 1980s the watershed management programmes, including reforestation activities, were implemented across the catchment. Reforestation programmes were targeted in degraded areas where they could potentially help in sedimentation control. A detailed classification of various land use systems was carried out by the Integrated Watershed Management Plan (IWMP) based on the LRMP (Land Resource Mapping Project) maps (Table 6.3, below). It shows the percentage of area covered by different land use types but not the intensity of vegetation cover. The catchment was covered by forest in most parts of the mountain slopes. Lower valleys and plains were largely occupied by croplands and human settlements. The forest area covered about 44% of the catchment, closely followed by cropland (42%) which includes sloping terraces, level terraces and valley terraces (DSCWM, 1992). Sloping terraces are the dominant agricultural type which alone occupied more than 80 percentage of total cropland coverage. Other major land use types were shrub land (9%), grassland (1.6%) and reservoir/lake (1.7%).

Table 6-3: Land use types of the Kulekhani catchment in 1991 (Source: DSCWM, 1992)

Land use & cover types	Area (ha.)	Percentage coverage of the catchment
Sloping Terrace	4254	34
Level Terrace	237	1.9
Valley	713	5.7

Terrace/Fans/Tars		
Forest	5455	43.6
Shrub-land	1147	9.2
Grazing and grass lands	200	1.6
Barren /Rock field	50	0.4
Lake	216	1.7
Gullies/Landslides	18	0.1
Others	210	1.7
Total	12500	100

In later years, various watershed conservation activities such as reforestation/afforestation and erosion control measures were implemented across the watershed (mentioned in section 6.4, above). Reforestation activities were carried out in shrub, grassland and barren areas. At the same time, most of the existing forest areas were transferred to local communities to offer them better protection and sustainable management. Such watershed management activities have had a positive impact on the improvement of watershed land cover.

We have also derived three major land cover types (i.e. tree, herb and bare) from the historical land cover maps (fig. 6.13, below). For the year 1978, we used LRMP maps of major land use classifications (LRMP, 1984). Similarly, for the year 1992, the land use map was derived from aerial photomaps (BIWMP, 2003). Finally, the land cover for the year 2012 is derived from the Google Earth digital maps (DigitalGlobe, 2012). The area calculation for each land use type is based on the aerial land cover. Since the sources of data are different, the land use system has to be interpreted with local realities.

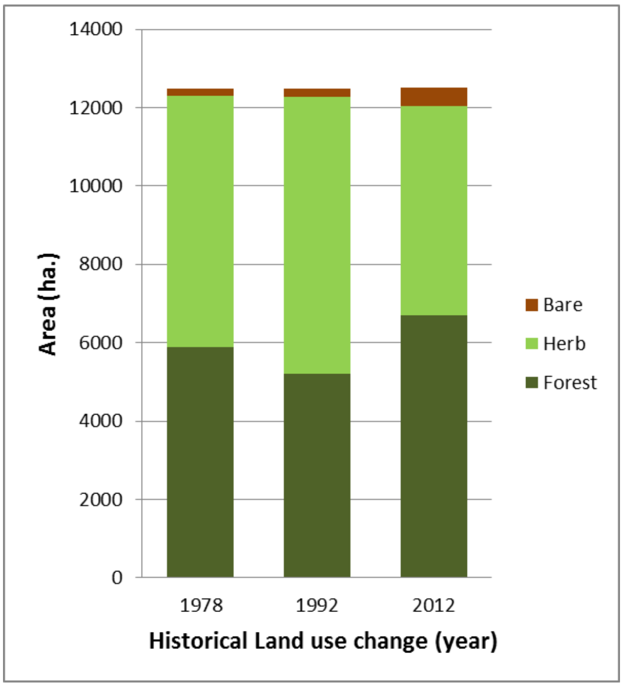


Figure 6-13: Historical land use change scenario at the catchment scale (LRMP, 1984; BIWMP, 2003 and DigitalGlobe, 2012)

The forest cover decreased by almost 13% between 1978 and 1992. At the same time, the herb cover (which includes cropland, shrubland and grassland) increased by 10%. In 1992, forest and herb covered areas took up about 42% and 47% of the catchment respectively. The rest of the area was occupied by reservoir and bare areas. In the following decades, the watershed conservation activities were increased through targeted watershed management programmes and the devolution of community based forestry management activities. By 2012, forest cover had been recovered and even increased to 54% in the catchment. In addition, herb cover decreased to 43% and bare cover, including reservoir, roads, human settlements and barren areas, is now at about 3%. During the last two decades, forest cover significantly increased through conversion of shrub and grasslands to forest land.

These statistics clearly reflect that various watershed conservation programmes have had positive impacts on land use systems. Upland communities play a central role in watershed management through direct or indirect involvement in different conservation activities. In addition, the community forestry management programme has played a bigger role in afforestation. Thus, the success of watershed conservation and the increased forest cover are closely related with the voluntary role of watershed communities.

6.5.3 The trend of reservoir sedimentation

The sedimentation survey was started in 1993 to improve the knowledge of siltation levels in the reservoir. The Nepal Electricity Authority (NEA), Department of Soil Conservation and Watershed Management (DSCWM) and the Nippon Koei Company have all been involved in the surveys at different time periods. Since 1996, the NEA has conducted the work on a regular basis. For the measurement of sediment deposition, the NEA (Nepal Electricity Authority) surveys ground profiles along the fixed survey lines by using both total station above water levels and echo-sounding under water (NEA, 2011).

The original capacity of the reservoir was 85.3 Mm^3, 73.30 Mm^3 and 12.00 Mm^3 of which were live and dead storage respectively, with reference to the level of water intake at 1471 m. The live storage is the amount of reservoir water available for HEP generation whereas the dead storage is the amount of water in the reservoir that is below the water intake. It can be clearly seen that the reservoir capacity had been decreasing rapidly in the early years of HEP operation but the rate slowed down in later years (table 6.5, below). From 1982 to 1996, the sediment deposition rate was very high and the reservoir lost 22 Mm^3 capacity (almost a quarter of its total) during that period. The major flooding disaster in 1993 and the problems that caused in the following years could have affected the situation. By 1996, the live storage capacity had reduced by 12.7 Mm^3 (17.3% of overall live storage) and the dead storage capacity by 9.20 Mm^3 (76.6% of overall dead storage). In that situation, the HEP authority had to increase the dead storage reference level to 1480 masl to maintain both live and dead storage volumes of the reservoir.

Table 6-4: Change in Kulekhani reservoir capacity on annual basis

Time Interval (*Month/ year*)	**Dead Storage Reference Level** (*masl*)	**Reservoir Capacity** (*M m^3*)		**Live Storage Volume** (*M m^3*)		**Dead Storage Volume** (*M m^3*)		**Sediment Deposition**		
		Total	**Reduction**	**Total**	**Reduction**	**Total**	**Reduction**	**Total** (*M m^3*)	**Average** (*m^3/ha*)	**Cumulative Average** (*m^3/ha*)
Design, '82	1471.00	85.30	0.00	73.30	0.00	12.00	0.00	0.00	0.00	0.00
Till Mar.'93	1471.00	83.10	2.20	72.30	1.00	10.80	1.20	2.20	176.00	16.00
Dec. '93	1471.00	78.30	7.00	70.70	2.60	7.60	4.40	4.80	384.00	46.00
Sept. '94	1471.00	67.80	17.50	61.30	12.00	6.50	5.50	10.50	840.00	107.00
Nov. '95	1471.00	63.80	21.50	60.80	12.50	3.00	9.00	4.00	320.00	122.00

Dec. '96	1471.00	63.40	21.90	60.60	12.70	2.80	9.20	0.40	32.00	116.00
Nov. '97	1480.00	63.19	22.11	55.55	12.70	7.60	9.45	0.20	16.00	110.00
Nov. '98	1480.00	62.63	22.67	55.20	13.09	7.42	9.62	0.56	44.80	106.00
Nov. '99	1480.00	62.64	22.66	55.66	12.59	6.98	10.07	0.66	52.80	99.91
Nov. '00	1480.00	62.38	22.92	55.58	12.67	6.80	10.25	0.26	20.80	95.73
Nov. '01	1480.00	62.36	22.94	55.57	12.68	6.79	10.26	0.02	1.60	91.03
Nov. '02	1480.00	62.30	23.00	55.56	12.69	6.74	10.31	0.06	4.80	86.92
Nov. '03	1480.00	62.27	23.03	55.56	12.69	6.71	10.34	0.03	2.40	83.08
Jan. '05	1480.00	62.25	23.05	55.54	12.71	6.71	10.34	0.02	1.76	79.54
Apr. '06	1480.00	60.52	24.78	54.71	13.54	5.81	11.24	1.73	138.08	81.94
Nov. '07	1480.00	60.33	24.96	54.57	13.68	5.76	11.24	0.18	14.56	83.07
Mar. '09	1480.00	60.23	25.06	54.53	13.72	5.70	11.35	0.10	8.00	7.94
Sept. '10	1480.00	60.00	25.30	54.22	12.03	3.78	13.27	0.24	19.20	19.05

(Source: NEA, 2003 & 2011)

Currently, the total reservoir capacity (including live and dead storage) is about 60 Mm^3. By 2010, the reservoir had lost a total volume of 25.3 Mm^3 (about 30% of its original capacity) for sediment deposition. It is estimated that the annual siltation till 2010 was about 937,200 m^3 for the entire catchment (NEA, 2011). The sedimentation trend for the last three decades clearly shows that there was a higher rate of sedimentation in the early years of its operation (Fig. 6.14, below). The highest rate of sediment deposition for the period between 1993 and 1995 was linked to the flooding disaster in 1993 and the higher rates of soil removal from the disturbed upland areas in the following years. However, future research would be required for a better understanding of such extreme events.

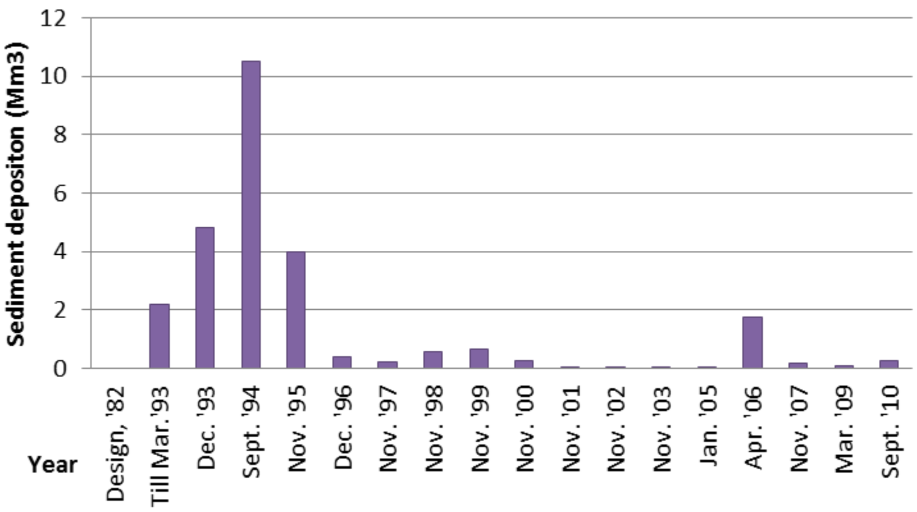


Figure 6-14: Annual sediment deposition trend of the Kulekhani reservoir (Mm3/year) (Source: NEA, 2003&2011)

In the recent decade (excluding the year 2006), the sediment deposition has become constantly low. The higher sediment deposition for the year 2006 might have been caused by major landslides triggered by the higher intensity of monsoon rainfall in previous years. The lower level of sediment deposition means a longer life span for the reservoir. As the sediment deposition is reduced, the overall capacity of reservoir has become better maintained in recent years (Figure, 6-15, below). The results indicate that conservation interventions might have had positive impacts on erosion and sedimentation control in the upland areas.

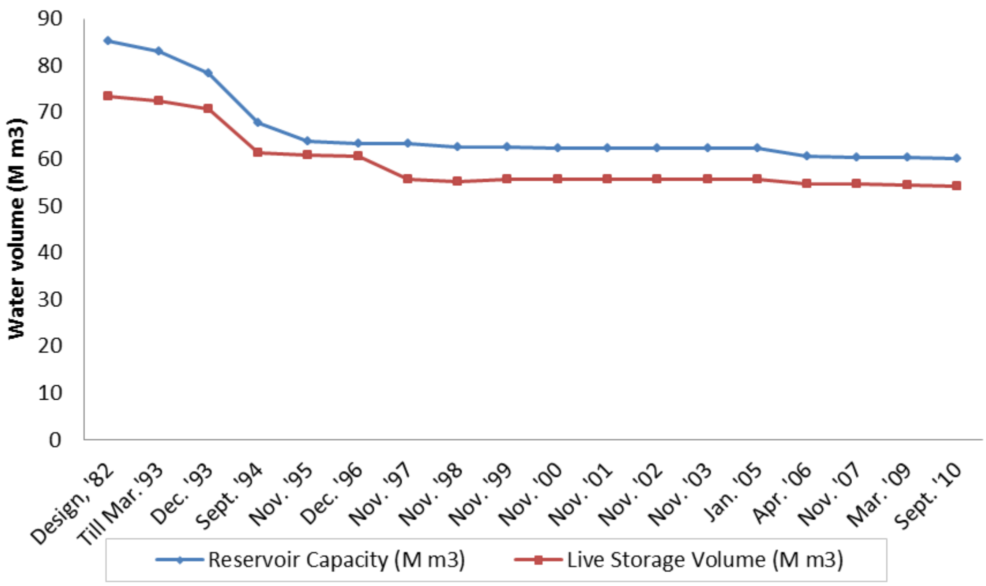


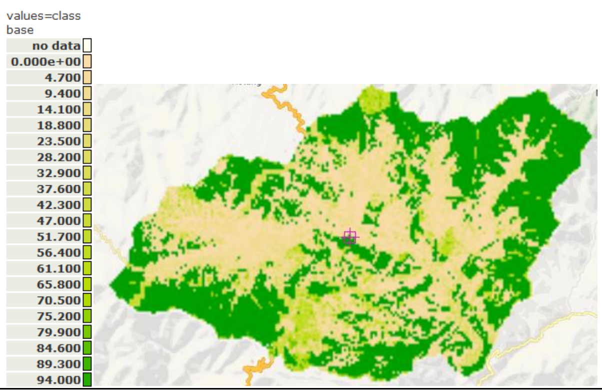
Figure 6-15: Change in reservoir capacity (in million cubic metres) (Source; NEA, 2011)

After the major flooding of 1993, watershed protection activities were implemented along with major infrastructural projects such as check dams and river embankments. In a broader scientific consensus, the better management of upland areas tends to improve the hydrological services of the catchment (see, Bruijnzeel and Bremmer, 1989). Local communities' efforts to protect catchment landscapes must have generated positive impacts on erosion control and sedimentation processes. The latter is also influenced by several other factors such as soil characteristics and geological features. Thus, we conclude that although there is a positive contribution of watershed conservation interventions (with the voluntary support of local people) in sediment control, future research would be needed to explore the links between better watershed conservation interventions and their impact on sedimentation processes.

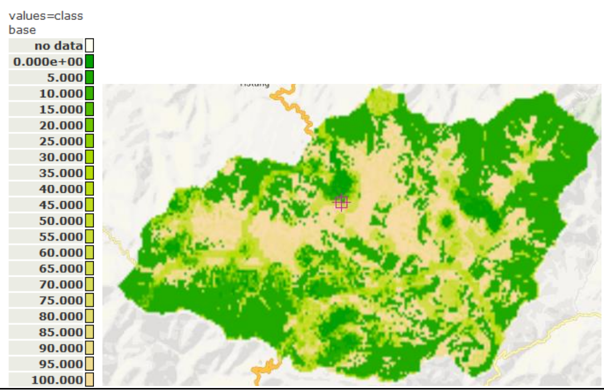
6.5.4 Modelling hydrological ESs using a future plausible LUCC scenario

To understand the likely change in future hydrological ESs, the research has developed a land use and cover scenario for the next 30 years. The baseline land cover of the catchment is derived from the 30 m resolution dataset of Landsat land cover maps representing the MODIS VCF Tree Cover layer (using circa 2000 and 2005 Landsat images) including the MODIS Cropland layer (Sexton et al., 2013). Based on existing conservation activities, primarily the successful implementation of a community forestry programme, we designed a 'forest growth' scenario to reflect a positive change in watershed conservation for the period. The scenario also assumes that the recently established PES based Environmental Management Special Fund (EMSF) would also support watershed conservation activities, primarily afforestation and reforestation programmes in the upland areas. Although the WaterWorld PSS is an advanced hydrological modelling tool used to assess different hydrological attributes, the biophysical and hydro-climatic dynamisms of the study catchment may affect various hydrological functions. Thus, the study suggests the use of modelling results with caution.

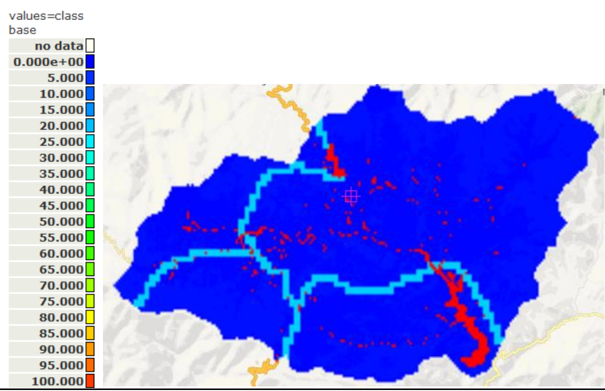
Based on the above assumption for future LUCC prospects, the Forest Growth scenario defines pixels as 94% trees, 5% herbs and 1% bare in areas of >10 degree slope gradient and where the baseline tree cover is more than 20%. Under this scenario, most of the forest growth takes place adjacent to the current forest covered areas and steep slopes (fig. 6.16, below). The percentages of tree, herb and bare cover in 'baseline' and 'forest growth' are presented in fig 6.14, below. The scenario leads to an increase in tree cover by 17%, a decrease in herb cover by 15% and an increase in bare cover by 1%. With the Forest Growth scenario, the catchment would have 48% tree cover, 40% herb cover, 5% bare cover and the rest occupied by water bodies. Herb covered areas are mostly filled with cropland and concentrated in the valleys and lower sloping terraces. Bare covered areas include all non-vegetated areas, primarily road networks, human settlements, barren areas and the Kulekhani reservoir.



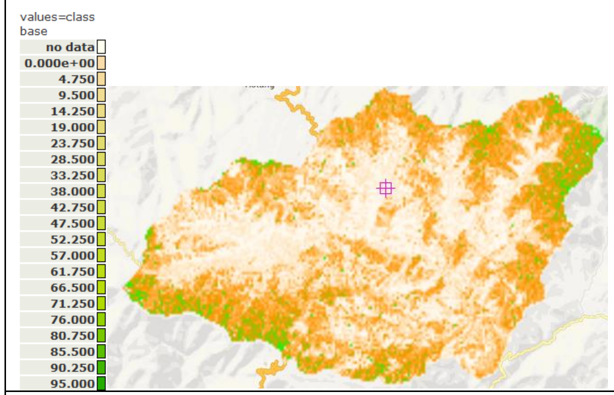
a) Tree cover (Scenario) (mean: 48%)



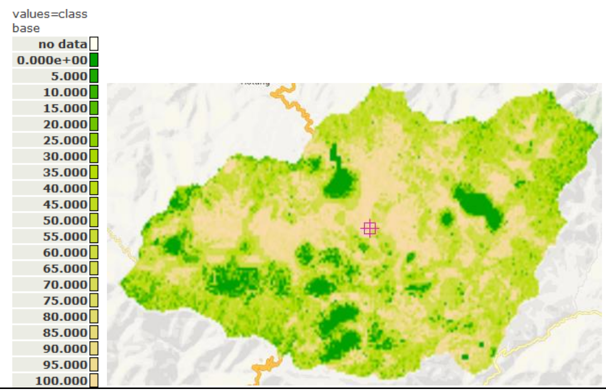
b) Herb cover (Scenario) (mean:40%)



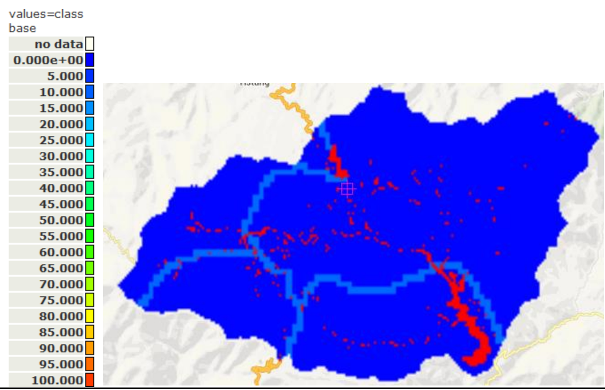
c) Bare cover (Scenario) (mean: 5%)



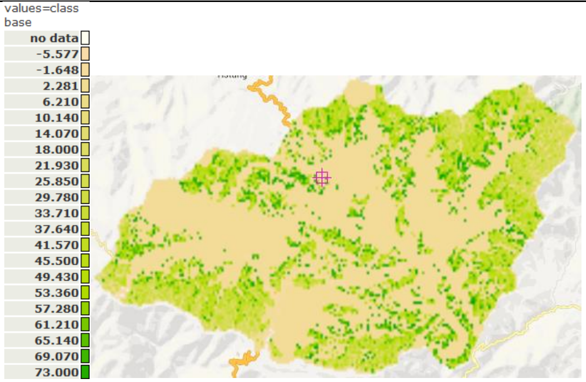
d) Tree cover (baseline) (mean: 31%)



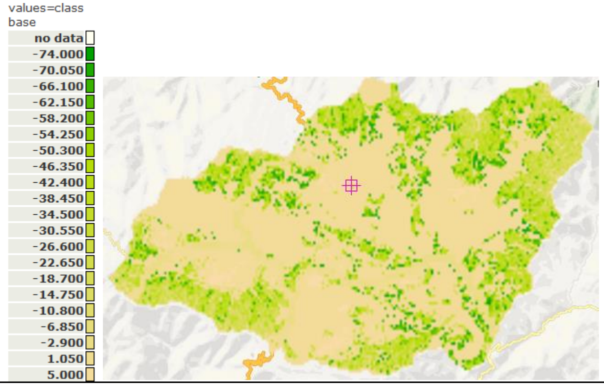
e) Herb cover (baseline) (mean: 55%)



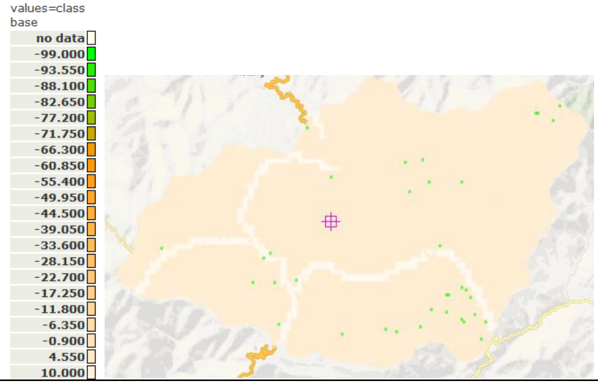
f) Bare cover (baseline) (mean: 4.2%)



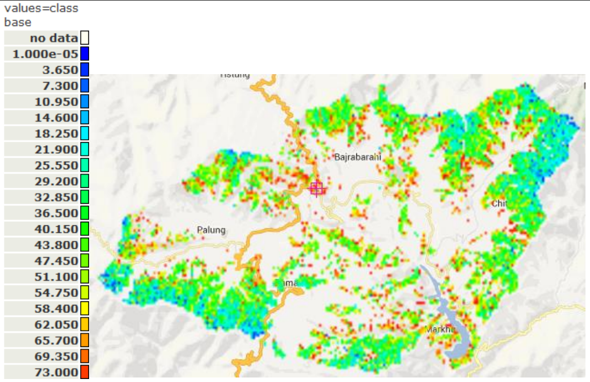
g) Change in tree cover (Scenario vs. baseline)



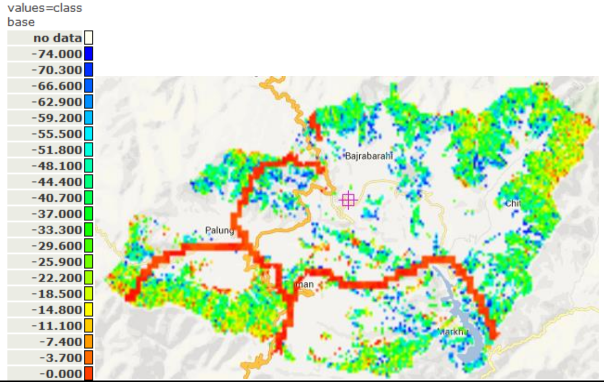
h) Change in herb cover (Scenario vs. baseline)



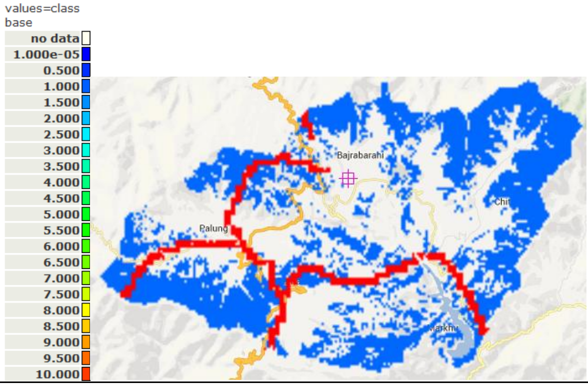
i) Change in bare cover (Scenario vs. baseline)



j) Positive change in tree cover (mean: 17%)



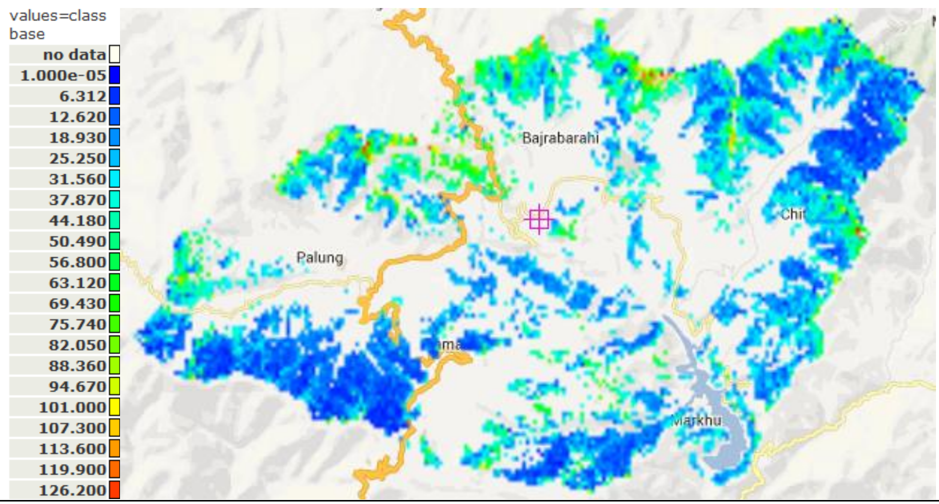
k) Negative change in herb cover (mean: -15%)



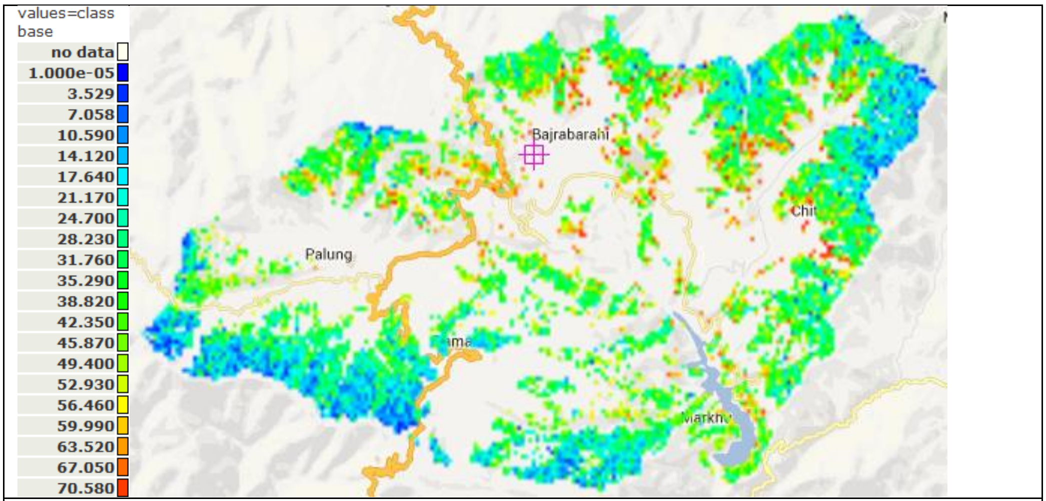
l) Negative change in bare cover (mean: -0.8%)

Figure 6-16: Change in vegetation cover under the 'Forest Growth' scenario (% land cover) (WaterWorld-V2, 2013)

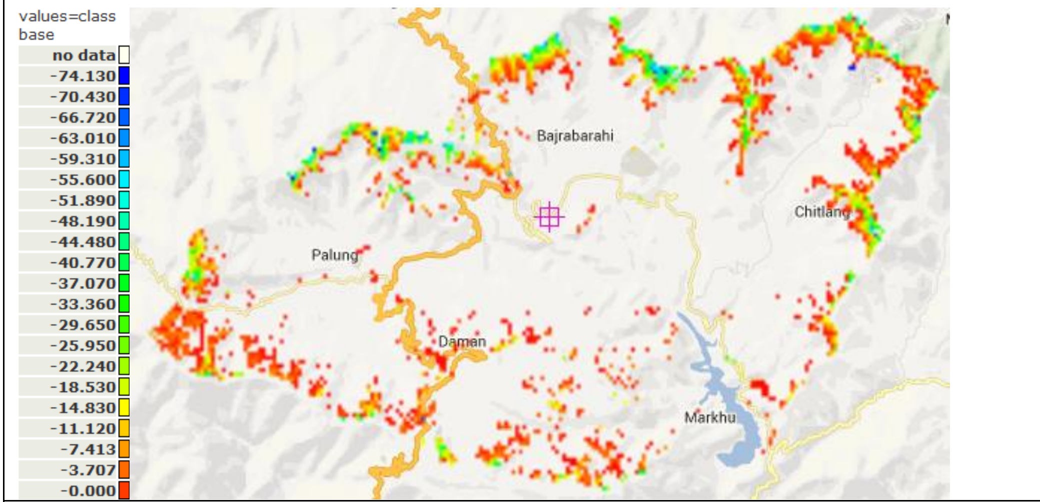
According to the WaterWorld PSS, by using this scenario, key hydrological fluxes such as evapotranspiration and fog interception will change to some extent (Fig. 6.17, below). This will lead to a mean increase in evapotranspiration for the area by 11 mm/yr (a total of 1.7 million m^3 for the catchment) and a mean increase of fog interception by 14 mm/yr (a total of 2.2 million m^3 for the catchment). Annual total AET would increase in parts of upland areas, especially along the mountain ridges where new forest growth would take place. Due to the higher slope gradient, these areas are less suitable for crop cultivation and better suited for Forest Growth. As the latter takes place in upland areas, the fog input (CWI effect) would also increase. However, due to opposing directions of change in ET and fog interception, the catchment would gain a small increase in mean annual water balance by 3 mm/yr (a total of 0.51 million m^3 for the catchment). In the catchment, the annual water balance would have both an increasing and decreasing trends depending on the intensity of AET and fog inputs in Forest Growth areas (Fig. 6.17c&d, below).



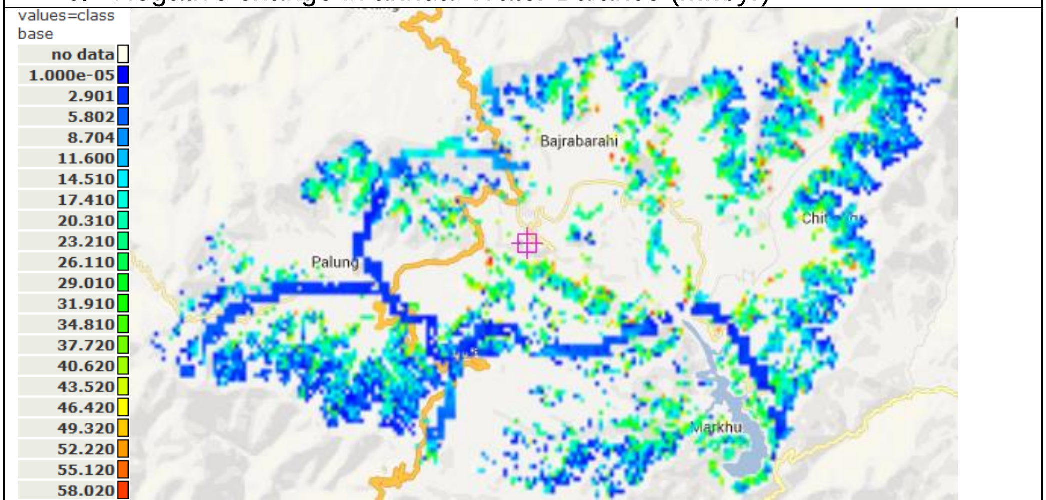
a. Positive change in annual AET (mean: 11 mm/yr)



b. Positive change in annual fog inputs (mean: 13 mm/yr)



c. Negative change in annual Water Balance (mm/yr)

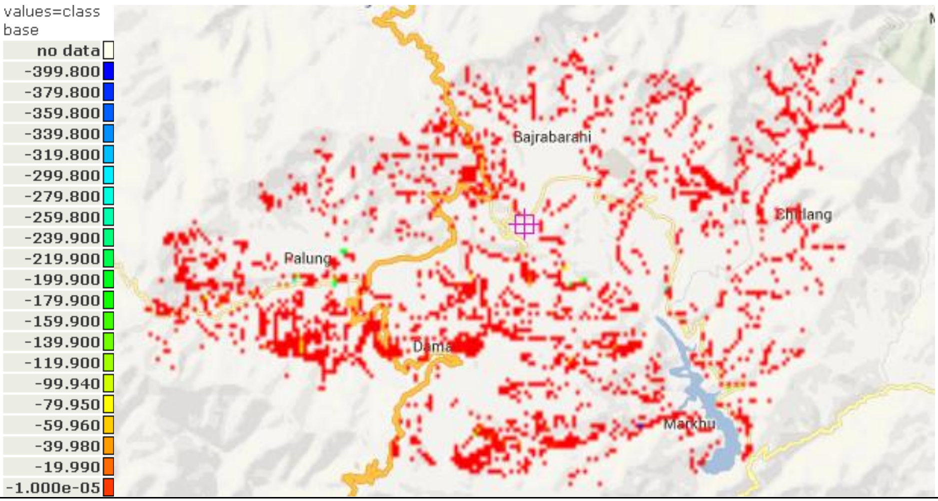


d. Positive change in annual Water Balance (mean: 3 mm/yr

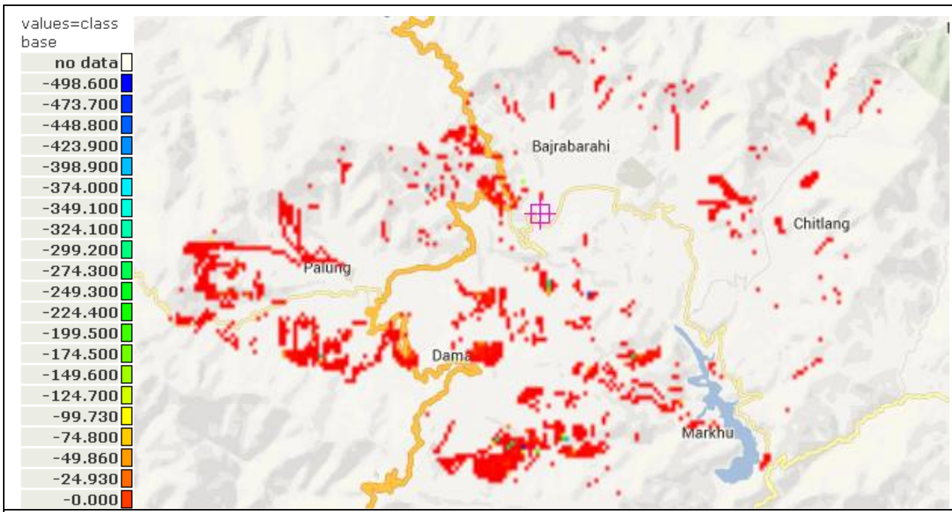
Figure 6-17: Change in quantitative hydrological ESs of Kulekhani catchment (WaterWorld-V2, 2013)

Considering the overall capacity of the reservoir at 83.1 Mm^3, the Forest Growth scenario would increase annual water balance by 0.51 Mm^3 which is an increment of 0.2% on current water balance. It shows a slight increase in water availability, and thus, a direct hydrological ESs benefit to the HEP operating company.

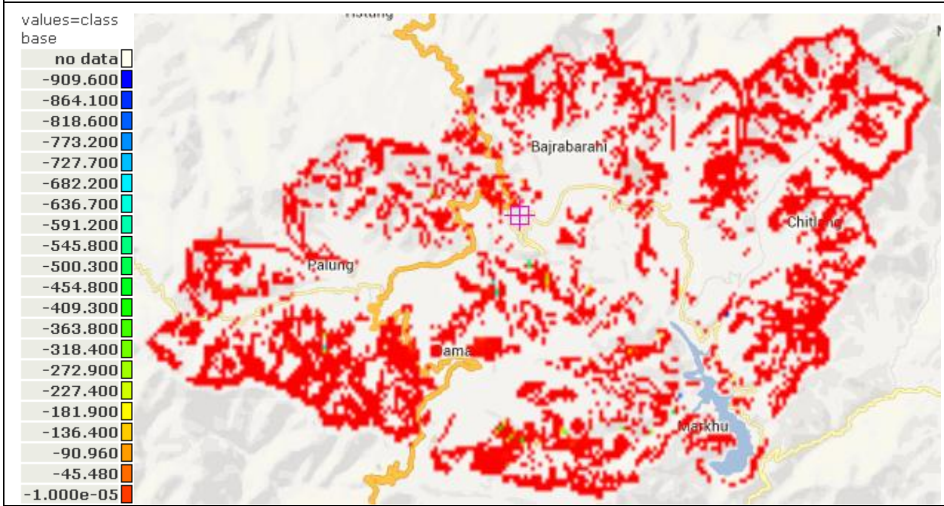
The study also assesses the change in hydrological quality of the catchment under the Forest Growth scenario. First, we quantified the changed annual total net soil erosion at the catchment scale. It decreased by 0.4 mm/yr (a total of 61,000 m^3 for the catchment). This proves that there is a decreased net soil erosion in parts of the catchment (Fig. 6.18a, below). The LUCC scenario indicated that forest growth would be better in these areas. Similarly, the annual total gross soil erosion would also decrease by 1 mm/yr (a total of 170,000 m^3 for the catchment) which is contributed by the slope stabilization in the west and south-west areas of the catchment (Fig. 6.18b, below). As a result, there would be lower soil deposition in the downstream reservoir by 1.4 mm/yr (a total of 230,000 m^3 for the catchment) (Fig. 6.18c, below). The distribution of decreased soil deposition is seen across the catchment but mostly occurs in improved forest covered areas. Finally, the modelling results also show that the change in human footprint on water at 2.2% (Fig. 6.18d, below). This is lower in the areas where forest cover is significantly increased and land use changed to 'natural' land cover. As a result, there would be lower human impact on water related ESs.



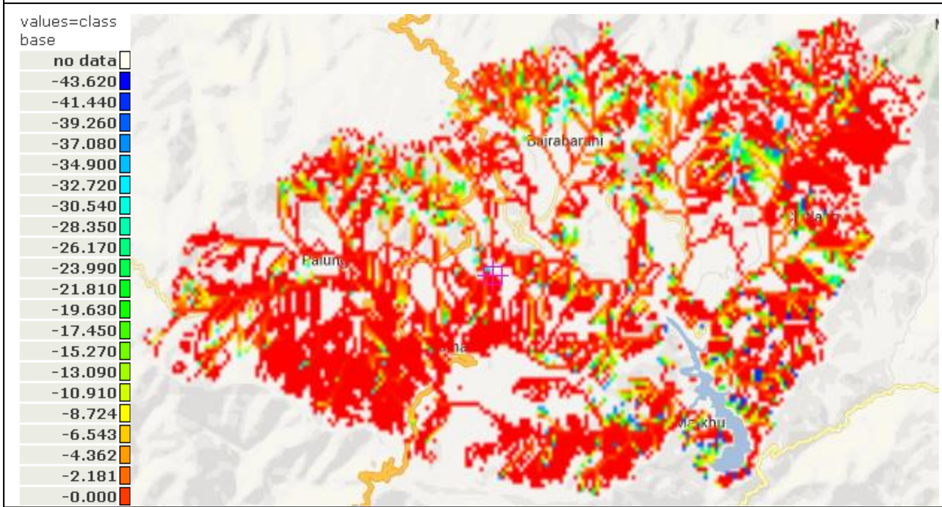
a. Change in annual total net soil erosion (mean: -0.4 mm/yr)



b. Change in annual total gross soil erosion (mean: -1 mm/yr)



c. Change in annual total soil deposition (mean: -1.4 mm/yr)



d. Change in human footprint (% contamination) (mean: -2%)

Figure 6-18: Change in hydrological quality/regulatory ES of the Kulekhani catchment (WaterWorld-V2, 2013)

The modelling results show that there would be a slight increase in water quantity (0.5 million m^3) as well as improved hydrological quality/regulatory services such as a lower human footprint, less net/gross soil erosion and a reduced soil deposition in the reservoir. Reduced soil deposition by 230,000 m^3 means the reservoir would retain the equivalent amount of water, which would enhance its lifespan along with the HEP project. Such improved hydrological ESs would directly benefit the downstream HEP operating company. Thus, the modelling results affirm that the Forest Growth scenario would improve the hydrological ESs of the Kulekhani catchment.

The modelling results show that the conservation interventions would have positive impacts on both quantity and quality related hydrological ESs. Although the increased forest cover would increase AET, the water loss is compensated by increased fog deposition in upland areas. The modelling of key hydrological ecosystem services has provided sufficient evidence that a better managed catchment will provide direct benefits to downstream beneficiaries. A substantial level of fog water inputs in higher grounds of the catchment is a major research innovation which has overall positive effect on water availability. Thus, watershed management activities would have to continue to improve water availability to the HEP authority but also a better quality of water services by reducing the sedimentation level.

6.5.5 Who benefits from the better hydrological ESs of the catchment?

Traditionally, water resources in the Kulekhani catchment were exclusively used for domestic needs and irrigated croplands in valleys and accessible terraces. After the development of the Kulekhani HEP in 1982, a reservoir was constructed to store available annual water balance and generate HEP. Since then, the Kulekhani HEP operating company (i.e. the Nepal Electricity Authority) has been receiving a substantial economic benefit from the HEP generation. Under the Electricity Act (HMGN/NEA, 1992), the hydropower project has to pay the central government NRs. 100 for each installed Kilowatt of electricity per year, plus 2% of the average tariff per Kilowatt hour for 15 years from the first commercial generation of the hydropower project. After 15 years, the project owner has to pay NRs. 1000 for each installed Kilowatt hour and 10% of the average tariff per Kilowatt hour. The Hydropower Development Policy (1992) waives the royalty on the amount of electricity used for the operation of powerhouse of the same HEP project (HMGN, 1992). After the enactment of the Local Self Government Act & Regulation (1999), 10% of the hydropower royalties shall be allocated to the hydropower housing district

(HMGN/MLD, 1999). In 2003, the Royal Ordinance issued has further increased to 50% that needs to be given to local governments. It further stipulated that 12% of the total royalties shall be given to the hydropower housing districts and 38% to the respective development region.

With the development of the HEP legislations, progress has been made to transfer the hydrological benefits to local governments. However, the hydro royalty has only been shared with the district and regional governments. The actual service providers (i.e. upland communities) have long been neglected from the real benefits despite their direct contribution towards the maintaining of hydrological ESs. Contemporary polices seem reluctant to share such direct benefits with the watershed communities. On the one hand, upland communities have compromised their potential to exploit watershed resources (particularly forest) for the sake of better watershed conservation. On the other hand, these communities are mostly disadvantaged groups and have limited livelihood opportunities. It shows that the catchment's better hydrological ESs are benefitting the downstream HEP company. There is very little or no benefit to upland communities. Therefore, sharing hydropower benefits with upland communities would achieve the twin goals of both improving hydrological ESs and enhancing local livelihoods in the upland areas.

6.5.6 Payment for ecosystem services (PES) initiative and policy implications

The Kulekhani catchment witnessed almost uninterrupted external support from various external agencies from the early 1980s until 2003. Since then, the catchment has not received any significant external support for conservation activities. Although those programmes immensely helped to improve the condition of upland land cover, there is no direct support to upland communities to maintain and improve those conservation successes. However, the upland communities started receiving PES payments since 2006 after a successful campaign led by the ICRAF (International Centre for Research in Agroforestry) - the World Agroforestry Centre and the Winrock International for a PES based voluntary share of HEP benefits to upland communities (Upadhyaya, 2007).

Rewarding Upland Poor for Environmental Services (RUPES) – a PES based action research project implemented between 2003 and 2006 – worked with central and local government institutions, upland communities, the hydropower company and NGOs to earmark a portion of hydropower royalties received by the local government as a reward to upland communities for providing environmental services. As a result, the Makwanpur District Development Committee (DDC) established an Environmental Management Special Fund (EMSF) to manage the PES payments (Upadhyaya, 2007 and Huang and Upadhyaya, 2007). The EMSF receives 20% of the royalty share (about US$54,000 per annum) to support conservation and development programmes in the catchment. The EMSF is managed by a multi-stakeholder committee representing upland communities, district government departments of forestry, soil conservation, agriculture and livestock. The hydropower authority and the Makwanpur DDC would evaluate and select projects (Upadhyaya, 2007). Hence, with the recognition of the upland communities' direct contribution towards watershed conservation, the main beneficiary (i.e. the Kulekhani HEP) and relevant government agencies agreed to implement a PES mechanism.

Although the PES scheme has been implemented, several challenges have emerged in terms of its better and equitable use for achieving both conservation and sustainable development goals. Like many other PES programmes around the world, the EMSF is not directly transferred from the beneficiary (the HEP authority) to service providers (upland communities). The payment comes through an intermediary (i.e. the DDC – the local government authority). The central government provides 12% of the total annual HEP royalty to the DDC authority, and from that, the DDC transfers 20% to the EMSF. Thus, the EMSF is partly a voluntary payment by the district government authority. It could be interrupted or withdrawn if the DDC authority believes the local efforts are not enhancing watershed conservation or negatively affecting existing hydrological ESs.

Although the condition of maintaining watershed ESs may encourage upland people to maintain watershed services, it also adds uncertainty to the programme. It may be unlikely that the DDC can change the scheme unilaterally since the local people's right to the fund are now recognized in the decision making process (Huang et al., 2009). However, a legislative would still be a better option for guaranteeing the fund transfer to the EMSF through intermediary or direct payment mechanisms. The upland communities' existing ability to manage the EMSF is also not fully developed since the catchment is a home to multi-ethnic communities with varying land tenure, education and engagement in the political process (Pandeya, 2005 and Upadhyaya, 2007), so there might be unfair competition for the fund. In this circumstance, the upland communities would require awareness raising and capacity building programmes on how to manage the EMSF efficiently and more equitably. Despite the current difficulties in the PES fund management, they could provide a long term solution for better hydrological ESs management. The PES mechanism has also created a space to involve all stakeholders in considering to improve the condition of watershed and associated hydrological ESs.

The modelling results for future plausible land cover confirmed that the increased reforestation activities have had a positive effect on water quantity and quality (sedimentation load and human footprint level). The north-east and west parts of the upland areas are contributing in creating an increased water balance which benefits HEP production capacity. These areas are protected by the community forestry programme. It has thus been proved that the recent conservation interventions have enhanced hydrological benefits. Such benefits can be maintained by the implementation of sustainable watershed management programmes. In that case, the better management of existing PES programmes will be an option.

6.6 Conclusions

The study assessed the hydrological ESs provided by the Kulekhani catchment, a human dominated mountain catchment in the middle-mountainous region of the Himalayas. It estimated currently realized hydrological ESs, particularly focused on the HEP benefits of the catchment. It also analysed the change in land use and cover of the last three and half decades (data available from secondary sources) to understand the hydrological impact of historical land cover change. The forest cover has been significantly expanded in recent decades. Available hydro-climatic and biophysical datasets (both from the SimTerra database and ground datasets) have been used to model the hydrological situation using the WaterWorld PSS to estimate the quantitative and qualitative hydrological ESs of the catchment.

Initially, the study estimated the baseline hydrological ESs and used a plausible land use change scenario (i.e. Forest Growth) to estimate its impact on hydrological ESs. This scenario would increase forest cover by 17%, mostly from the increased amount in existing upland area patches. As a result, the AET would increase by 11 mm/yr (a total of 1.7 Mm^3 for the catchment) which is about a 6.2% annual increase. At the same time, the fog inputs would increase by 14 mm/yr (a total of 2.2 Mm^3 for the catchment) which is about a 5.3% annual increase. The annual water balance would increase by 3 mm/yr (a total of 0.51 Mm^3 from the catchment) which is about a 0.2% increase in the baseline annual water balance. The increased water availability is directly contributed by the increased annual fog inputs (supported by increased forest cover in the upland areas). In addition, a reduced annual gross soil erosion of 170,000 m^3 per year and a reduced annual total net soil erosion of 61,000 m^3 would lower the sediment deposition process in the downstream reservoir. Annual total soil deposition is decreased by 230,000 m^3. The human footprint would also decrease by 2% from the baseline as the forest cover is increased in upland areas. Thus, the study concludes that the 'Forest Growth' scenario would improve both hydrological ESs (both quantitative and qualitative) benefits to downstream HEP operating companies. Since the model is largely reliant on globally available datasets for biophysical and hydro-climatic characteristics (except for the collected ground rainfall data for selected catchments), the modelling results must be interpreted with caution. In addition, the impact of fog inputs have not been tested for the region and need to be verified with ground based experiments.

Although the current PES programme is a voluntary payment, the fund could play a major role towards conservation sustainability. The current PES mechanism has various challenges at local level such as uncertainty in fund transfer and the lack of local capacity to use it more equitably. Despite these challenges, the PES could still offer opportunities to both parties (upland communities and downstream beneficiaries) to work together for better management of watershed conservation programmes and further improvement of hydrological ESs.

Chapter 7 Conclusions and Future Research Recommendations

7.1 Research aim and objectives

The main aim of the research was to improve the understanding of key hydrological ESs produced by the IGB catchments at different geographical scales through a process-based hydrological modelling as well as in-depth analysis of key hydrological attributes. To address the aim of the research, the thesis set the following key objectives:

i) To model crop evapotranspiration and its potential impact on future water availability at the IGB administrative region scale.

ii) To assess water supply provisioning services of a protected area catchment.

iii) To assess hydrological ESs and the long-term prospect of a Payment for Ecosystem Services (PES) in a human dominated catchment.

At selected catchment scales, the research also focused on the contribution of fog water inputs into annual water availability. Similarly, ESs based watershed management approaches - particularly payment mechanisms - are closely observed for the enhancement of hydrological ESs and the sustainability of watershed conservation.

7.2 Main conclusions and developments

The thesis presents research conclusions and some significant developments within the context of hydrological ESs of the IGB catchments and local mountain catchments.

a) Crop ET consumes the majority of annual AET in the IGB catchments, especially in food producing regions such as Haryana, Punjab (India), Uttar Pradesh, Punjab (Pakistan), Bihar and Rangapur-Rajshahi. The thesis also demonstrates the important role of crops carrying hydrological ESs (in embedded form as 'Virtual Water') to consumers within and beyond basins. It is also clear that projected future cropland cover scenarios would exacerbate the water deficiency related problems already experienced in the north-western region of the basins. The research emphasizes the needs for an efficient use of freshwater resources in those areas. Finally, it is concluded that the ET services should be integrated into hydrological ESs research.

b) The protected area catchment is supplying important water provisioning services to downstream urban centres. Modelling results show that the improved LUCC scenario has produced increased water quantity and reduced sedimentation/erosion levels in the streams. Fog water input has played a key role in offsetting the loss of water balance due to increased ET on afforestation. The research also concludes that at the sub-catchment where human settlements exist, an integrated watershed management scenario would generate increased water availability compared to complete reforestation of the sub-catchment. Since it is extremely challenging to relocate such human settlements, a payment based mechanism such as PES could help to maintain water quantity and quality through supporting upland communities' watershed management programmes.

c) The research also concludes that the Kulekhani catchment - a human dominated area - has provided increased water quantity and reduced sedimentation processes to a downstream HEP project. Conservation activities in the catchment have had a positive impact on both water quantity and quality (erosion and sedimentation control). Sedimentation has also reduced in recent years, though this may have more to do with sediment mobility on the landscape following an extreme event in the year 1993 rather than increased tree cover. Modelling of plausible LUCC scenarios confirm that the continuation of watershed conservation activities would further improve the water quantity and quality (reducing sedimentation and human footprint levels). Thus, the research also concludes that the existing PES scheme could be a good policy mechanism in maintaining hydrological ESs.

The thesis has discovered some significant developments in the context of hydrological ESs as well as water resources policies at regional and local scales. Cropland water consumption plays an important role in water resources related policies of the IGB catchments. Since most of the lowland plains are already occupied as cropland, any future growth would be in the upland region of the basins. Such cropland expansions in middle regions such as Madhya Pradesh, Himachal Pradesh, Uttrakhand and Nepal would consume more water in crop ET processes and this phenomenon will create water deficiency in downstream regions.

Another major development of the research is the positive contribution of fog water input (CWI effect) in the middle-mountainous region. The thesis concluded that there is a good amount of fog water inputs contributing toward increased water availability in selected local catchments. Although the evapotranspiration rate increases with forest cover, an added increase in fog water inputs make an overall positive contribution in increased forest cover to the annual water balance. This research development has opened up a debate about the potential contribution of such hydro-climatic and biophysical characteristics in watershed management policies. However, the thesis clearly suggests the need for some ground level experiments to verify the actual contribution of fog inputs to the overall water balance.

There is a direct correlation between improved LUCC in upland areas and increased hydrological ESs in the selected catchments. Various conservation interventions implemented in protected areas and human dominated watersheds have had positive impacts on quantity and quality related hydrological attributes. It is proven by the modelling of hydrological ESs in plausible LUCC scenarios. In Sundarijal, a sub-catchment of the SNNP area, integrated watershed management scenarios generate increased water quantity by 6,100 m^3, a better quality of hydrological ESs such as decreased human footprint by 0.24% and less soil erosion by 36 mm/yr. Similarly, in the Kulekhani catchment, with the Forest Growth scenario, the catchment will produce 0.5 Mm^3 of additional water for the HEP reservoir. Human footprint has decreased by 2% and gross soil erosion is down by 1%. This evidence clearly supports the need for forest conservation in the middle-mountainous region.

The research also concludes that the PES based mechanism would help conservation activities in the selected catchments. Although the payment mechanism from ESs beneficiaries can be an attractive option for watershed management, there are still many challenges in terms of their role in watershed conservation and sustainable development. Thus, the prospect of the PES programme for watershed conservation and sustainable development needs further study.

7.3 Summary and future research recommendations

Various research findings have highlighted the huge scale of freshwater consumption in croplands, for example, green water use in rain-fed agricultural systems (Rockstrom et al., 2007) and groundwater extraction for intensive crop cultivation (Mukherji et al., 2005 and Shah et al., 2007). These have resulted in water scarcity as well as increased pressure on freshwater resources in parts of the IGB floodplains

(Sharma et al., 2010). In addition, Nellemann and Kaltenborn (2009) pointed out the potential future water crisis in the region due to the unprecedented level of demand not only from the croplands but also from all the other water use sectors. Despite the clear recognition of the potential future water crisis, there were limited attempts to explore the spatial distribution of cropland water consumption at the administrative region scale. Considering the research need, this thesis has assessed current and future cropland ET for the IGB administrative regions. The findings would help to fill the research gap of crop ET related hydrological ES. In the IGB catchment, the current use of water resources in the agricultural sector is hugely variable at the regional geographical and administrative levels. The modelling results show that the projected cropland growth will have a significant impact on water allocation across the basin. The research highlighted the potential change in water balance locally and in the downstream areas. Modelling results made an important scholarly contribution to the hydrological debates on over-allocation in the IGB. The research findings could also support agricultural water use policies in the region.

Hydrological modelling of a PA catchment (with a significant human population in a sub-catchment) has revealed that the selected sub-catchment is supplying important hydrological ESs to local and downstream beneficiaries. Using two different plausible LUCC scenarios: i) an integrated watershed management approach with human population, and ii) reforested catchment without human population, the research has concluded that the better implementation of an integrated watershed management programme would enhance the hydrological ESs. It has also concluded that water availability would increase in the integrated watershed management scenario but may diminish the water quality due to the presence of human footprint on water quality. Upland communities are an integral part of the catchment so their relocation could be a contentious issue. Thus, conservation programmes need to be better integrated with the local communities to minimize such effects.

In the middle-mountainous region of the Himalayas, water resources are heavily exploited for various uses. Upadhyaya (2007) and Huang et al., (2009) assessed hydrological ESs of a human dominated mountain catchment and argued for a PES-based mechanism to continue conservation activities and to improve local livelihoods. However, there was a profound gap of site scale detailed and process-based modelling of hydrological attributes (both quantity and quality) which is crucial to better understanding potential change in hydrological ESs in the context of plausible future LUCC scenarios. Previous assessments of hydrological ESs were largely based on assumptions or rules of thumb of the positive hydrological effects of conservation interventions. Upland communities' role in hydrological ESs are being broadly agreed in policy level (van Noordwijk 2005 and Upadhyaya, 2007) but the positive changes in hydrological ESs (estimated in both catchments) have strengthened the scientific argument of impact through improved hydrological ESs and also further supported the case for a payment for hydrological ESs. The research concludes that community based conservation efforts have improved quantity and quality related hydrological attributes. Since external support for the continuation of watershed conservation activities is not guaranteed, a share of hydrological ESs benefits from downstream beneficiaries would make conservation programmes more sustainable in the future.

The role of fog water inputs has been examined to a large extent for the tropical mountainous region (for example, Mulligan and Burke, 2005 and Bruijnzeel et al., 2011). However, there is very little effort made so far to estimate the level of fog water contributions in the water balance in the middle and high-mountainous regions of the Himalayas. Apigian (2005) argued that there is a huge prospect for fog water collection in the water deficient high mountainous areas. The modelling results have supported the fact that there is a substantial level of fog input (up to 11% of annual water balance) in the region. However, ground experiments would be needed to test the actual level of the contribution estimated in this research. Such experiments would eventually make a major contribution in the hydrological research of the region as there is perhaps a misconception that the increased forest cover may diminish the water availability as argued by Calder (2002). Thus, the research findings have improved the better understanding of water related ESs of the middle-mountainous area of the Himalayas, opening up the debate.

Based on the thesis conclusions and key research developments, we recommend the following key research needs to explore further some important aspects of hydrological ESs for these basins.

i) In the IGB scale, due to higher consumption of water in agricultural land, there could be direct or indirect impacts on other hydrological ESs, locally and downstream. On that basis, it is necessary to explore the likely impacts on other critical hydrological ESs such as the drinking water supply to rapidly growing urban centres, river diversion for HEP projects and the environmental flows required to maintain riparian ecology and aquatic habitats.

ii) This research revealed the significance of fog water inputs (or CWI effects) in annual water balance for the middle-mountainous region of the Himalayas. However, the modelling results would require ground based experiments to verify the actual contribution of fog inputs to annual water balance. Thus, the research suggests an experimental measurement of fog inputs at the site scale.

iii) The research also found that the hydrological ESs of the mountain catchments clearly improved due to an increased forest cover in upstream areas. Those improved services are enjoyed in the downstream areas (drinking water supply of the SNNP catchments) and beyond (HEP generation of the Kulekhani catchment). A self-sustaining PES mechanism for the maintenance of hydrological ESs (with the participation of upland communities) is a good strategy for securing hydrological ESs in long-term. However, policy and decision-making bodies may require more detailed analysis of ground based experiments. In addition, the PES mechanisms are not straightforward since they are highly contextual and any PES programme may need to address different local issues such as people’s awareness and institutional capability for achieving conservation and livelihood improvement goals. Thus, although it is necessary to estimate quantitative and qualitative hydrological ESs of a catchment while designing a PES programme, a detailed understanding of local issues is also equally important to make PES programmes sustainable and more successful in the future.

Approaches to managing hydrological ESs (including the PES programmes) require a quantitative assessment of available hydrological attributes (fluxes) provided by different conservation practices as well as future plausible LUCC scenarios. Currently, there is still a profound gap in such assessment at the local catchment scale because of a lack of data and low capacity in the use of geospatial methods. At the local scale, although the research collected some ground data such as rainfall records to improve the input datasets, the model had to rely on global datasets to a great extent. The findings should be interpreted with caution and additional local datasets would require improving the hydrological ESs assessment.

The contribution of fog inputs is debatable as they are estimations based on the global model which has not been tested at the ground level in the middle-mountainous region of the Himalayas. It is therefore suggested that the fog input measurement at the site scale would be a useful next step. As the area is densely populated, any change in water availability would have a direct impact on many beneficiaries. Increased fog input is influencing water quantity and where it is higher than the AET, these areas are benefiting from the increased water availability. Similarly, the qualitative hydrological ESs such as human footprint, soil erosion and sedimentation processes also need to be tested with site scale experiments. With such experiments and the collection of improved ground datasets in future, the hydrological ESs assessment of conservation actions will become more robust.

Finally, the research has contributed to the advancement of scientific knowledge of quantity and quality related hydrological attributes that underpin valuable hydrological ESs in the IGB catchments at different geographical scales. The level of water consumption is very high in croplands distributed in lowland flood plains. Projected future cropland scenarios would further affect water availability in parts of the basin. The research also stresses that the crops are carrying water related ESs (embedded in the form of 'Virtual Water') and thus opening up a new paradigm of research in hydrological ESs. A detailed assessment of hydrological ESs of selected mountain catchments has clearly revealed that conservation activities have played a positive role in the production of improved hydrological ESs provisions. A substantial level of fog water inputs from mountain forests has proven the exceptional case for watershed conservation activities in the mountain catchments. Despite the challenges, the research has also supported the PES based mechanisms to ensure hydrological ESs of selected catchments in the long-term.

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Appendix I: A sample questionnaire for the better understanding of freshwater ecosystem services provided by the Shivapuri-Nagarjun National Park

The purpose of this questionnaire is to better understand dependence upon water based ecosystem services deriving from the Shivapuri-Nagarjun National Park (SNNP). Collected information will be treated as confidential and used for the academic research.

1. Personal information

Occupation: Age:
Gender: Number of dependents:
Number of people in household: (adults ____) (children_______)
Residency: (born here / Migrant) if migrant, year of your first arrival in this place:

2. Freshwater uses and consequences	
Key questions	**Description**
2.1) What do you use water for: (tick all that apply)	Irrigation of crops Water for livestock Domestic use (drinking) Domestic use (cooking and washing) Sanitation Other (please specify)
2.2) Where do you get your water? (rank in order of priority 1=highest).	From springs, well, borehole From a piped supply or tap From rainwater (coming through the roof of a house) From river, stream, dam, lake, pond Others (please specify)
2.2) Where do you get your water from for each of the above uses? (if several sources for each use, rank in order of importance)	Irrigation of crops______________________ Water for livestock_____________________ Domestic use (drinking) _____________________ Domestic use (cooking and washing) _________________ Sanitation_____________________ Other (please specify) _____________________ 1. From springs, well, borehole 2. From a piped supply or tap 3. From rainwater (coming through the roof of a house) 4. From river, stream, dam, lake, pond 5. Others (please specify)
2.3) If your main source of water runs dry or becomes unavailable what are the	From springs, well, borehole From a piped supply or tap From rainwater (coming through the roof of a house)

alternative sources of supply?	From river, stream, dam, lake, pond Others (please specify) There is no alternative
2.4) How would the loss of the main supply affect you most? (rank in order of priority 1=highest)	I would have less water I would have water of lower quality I would have to spend more time obtaining water I would have to spend more money obtaining water It would not affect me

3. Freshwater quantity, seasonal use and payment mechanism	
Key questions	**Your opinion**
3.1) Do you know how much water you use?	YES/NO
3.2) If yes, how much water do you use (litres or other stated unit) for each of the uses listed in 2.1?	
If you don't know how much water you use: 3.3) If you have no water supply in your dwelling, how often do you collect water per week? How many buckets/containers do you collect? What size are these?	
3.4)If you have no water supply in your dwelling, how much time do you spend collecting water each time?	
3.5) Does your household use less water in dry seasons? If yes, how much less (in percentage)?	
3.6) Do you pay for your water?	YES/NO
3.7) If yes, how much do you pay?	
3.8) How do you pay for your water consumption? Is it a fixed price per unit or per year or other?	

4: Payment for water	
Key questions	**Your opinion**
4.1) Do you know about the Shivapuri-Nagarjun National Park? What do you think of it?	

4.2) Do you use water coming from the park? If yes, what do you use it for? (rank in order of priority 1=highest)	Irrigation of crops Water for livestock Domestic use (drinking and cooking) Domestic use washing Sanitation Other (please specify)
4.3) What are the benefits and problems of water coming from the Park? Is it regular, cleaner......or with high sedimentation, poor quality........	Benefits: Problems:
4.4) Who else uses water from the Park?	Others in the same village, in other villages, upstream of you, downstream of you Other (please specify)
4.5) Who manages the water resources in this area? (rank in order of priority -1 highest)	National water authority District water authority Park authority Local community Others (please specify)
4.6) How do they maintain the water resources? (rank in order of priority 1=highest)	By managing land use By managing manures, herbicide and pesticide use By reforestation By building water infrastructure (treatments plants, wells, dams, pipelines) Other – describe

5. Land use change and resulting impacts on watershed ecosystem services		
Key questions	**Change**	**Reasons**
5.1) In your opinion, how have and will the following land covers change in the last 20 years? i) Forest land ii) Shrub land iii) Grass land iv) Crop land v) Others (..................)	Increase, no change or decrease	
5.2) In your opinion, how have and will the following land covers change in the next 20 years? i) Forest land	Increase, no change or decrease	

ii) Shrub land iii) Grass land iv) Crop land v) Others (..................)		
5.3) Have you noticed more or less land sliding and soil erosion on your fields in the last 20 years?	Increase, no change or decrease	
5.4) Have you noticed fewer or more droughts affecting your fields in the last 20 years?	Increased, no change or decrease	
5.5) Have you noticed any change in the water quality affecting your drinking water supply in the last 20 years?	Increased, no change or decrease	
5.6) Have you noticed any change in the water availability in the last 20 years?	Increased, no change or decrease	
5.7) Have you noticed any change in the seasonal availability of water in the last 20 years?	Increased, no change or decrease in which months/seasons	

6. Conservation status and the current state of hydrological ES	
Key questions	**Description**
6.1) Why is SNNP now protected? (order by priority 1=highest)	For its biodiversity and species For the scenic quality of its landscapes For the quality of water that it provides For reducing hazards like landslides and floods For its spiritual and cultural value Others (please specify)
6.2) What is your experience whether conservation approach has increased the water quantity or improved the water quality or no change at all?	Which of the following has the protection of SNNP led to (tick those true): (a) increased water supply (b) decreased water supply (c) no change in water supply (d) increased water quality (e) decreased water quality (f) no change in water quality (g) more river water in the dry season (h) less river water in the dry season (i) no change in river water in the dry season (J)Others (please specify)
6.3) Is your water treated to remove sediments and contaminants? **(yes/no)**	Ill health Lack of usable water Technical problems with water distribution or

Do you have problems with water quality being poor? **<u>(yes/no)</u>** What implications does this have? (list in order of priority 1 = highest)	irrigation systems others (please specify)

Name of Interviewer:.................................. Date:......................

Location:...

Appendix II: *AGUAANDES/WATERWORLD VERSION 2 MODULES*

Model Documentation

Version 2 of the AguAAndes/WaterWorld is still in development and beta testing with a small group of users. It builds upon version 1 by adding components for soil transportation and deposition to the soil erosion equations of version 1. Version 2 also adds an energy balance based snow and ice module, some changes to the way evapotranspiration is handled and a module for the spatial distribution of water quality. As well as the climate and land use change scenarios and policy options available for application in version 1, version 2 also incorporates modules for understanding the impact of land and water management interventions including bench terraces, fanya juu/bari terracing, check dams and existing or new reservoir dams.

MODULE: Soil Erosion, deposition and transportation

Full wash erosion, transportation and sedimentation model

Erosion according to Thornes (1990), E=kQmSne-0.07Vc

Transport capacity (Tc) according to stream power (Q, slope).

Sediment transport (S)=min (sediment from upstream+local erosion, P)

Sediment deposition where S>P

MODULE: Snow and ice

Snow and ice model

Initial monthly snow cover according to MODIS

New snow is precipitation where T<<0

Full energy balance for snow accumulation and melting (after Walter et al. 2005)

MODULE: Water quality

Water quality (human footprint on water)

Calculates the % of water at a point which fell as rain on point and non-point potential sources of contamination upstream

MODULE: Land and water management

Land uses - as well as land use being defined by the cover of Tree, Herb and Bare functional types, land use can also be defined by the land use type which can be one of Pasture, Cropland, Natural, Protected, Mining, Roads, Urban, Oil & Gas. These types affect the water quality indices. The initial values for these covers are set according to available input maps but the covers can be changed with the land cover and change policy options.

Land use intensities - each land use has an associated intensity of use. This intensity is set to 1.0 by default for all land uses. The intensity value can be changed in order to reduce intensity (for example eco-efficient agricultural practices) or increase intensity (particularly destructive mining techniques).

Riparian buffer strips -
Check dams -
Bench Terracing -
Fanya Juu -
Eco-efficient agriculture-
Water use -
Water treatment-
Sanitation –
Hydropower or storage dams-

MODULE: Mining and Oil and Gas

AGUAANDES/WATERWORLD VERSION 1 MODULES

Model Documentation

This section describes the science, equations and assumptions behind the modules and submodules used. Version 1 of AguAAndes/Waterworld is a sophisticated model of spatial water balance which has been developed for data poor and spatially complex and heterogeneous environments. The model includes modules for distribution of rainfall through interaction with wind, occult precipitation through fog inputs, solar radiation receipt, potential and actual evapotranspiration on the basis of climate and vegetation cover, water balance and its cumulation downstream as runoff. There is also a simple model for soil erosion. The model requires some 140 inputs maps (all of which are provided with the system, globally) and calculates monthly and annual hydrological variable including water balance, runoff and soil erosion for a baseline representing year 2000 land cover and mean 1950-2000 climate. Users can run scenarios for climate change and land use change and examine the impact of these on hydrological ecosystem services including water quality and seasonality. Given the lack of global data on groundwater resources AguAAndes/Waterworld does not simulate subsurface hydrological processes associated with flows in soil and groundwater.

MODULE: hydrology

SUBMODULE: Atmosphere

Surface area

True surface areas (as opposed to planimetric areas) are calculated with the triangle method (Jenness, 2004). These are important for the accurate representation of surface area in montane environments. True surface areas can be 1.3 times the planimetric surface area for very steep rugged slopes.

Vegetation

Tree, herb and bare percentages from MODIS VCF are converted to fractions

Timesteps

The model iterates between four diurnal and 12 mensual timesteps (4 in each month) for a total of 48 timesteps for a complete run.

Input climate data

Key assumption : Winds bend around topography, taking the path of least resistance. It is sufficient to model these changes in direction without accounting for concentration (funnelling effects)

Wind directions are read and converted to the appropriate topographically affected wind direction by reading the appropriate wind direction file. Based on this wind direction, the appropriate TOPEX value is read from the topex files. Note that the wind direction file BLWind mis the directions that wind is going to whereas in the

delivery model windspeeds are specified as directions that wind is
coming from. Relative humidity, temperature, diurnal temperature range, wind speed precipitation and extraterrestrial solar radiation are read from the appropriate files

Input cloud cover data for time of day and season

Key assumption : The MODIS data represents well the pattern of atmospheric cloud, where atmospheric cloud has formed and terrain level conditions are condensing (i.e. above the cloud base), this cloud is likely to be present at ground level. MODIS derived cloud cover is read with the overall annual average value modified by seasonal and diurnal correction factors.

Temperature, dewpoint and liquid water content

Key assumption: Cloud liquid water content is proportional to absolute atmospheric humidity.

Temperature is modified according to the diurnal temperature range as follows:

```
Tmp=if(Hour eq 1 then Tmp-(0.25*DiurnalTRange) else
        if(Hour eq 2 then Tmp else
        if(Hour eq 3 then Tmp+(0.25*DiurnalTRange) else
        if(Hour eq 4 then Tmp
                ))))
```

Dewpoint and vapour pressure are calculated according to:

es=exp(26.66082-0.0091379024*(Tmp+273.15)-(6106.396/(Tmp+273.15)))

where

Tmp = temperature (C)

Es = saturated vapour pressure (mb)

RH = relative humidity (%)

E = vapour pressure (mb)

Air density and absolute humidity are calculated as:

AirDensity=(MSLP*100)/((Tmp+273.15)*287)

Where

AirDensity = kg/m3

whereby LWC varies linearly with AH under the assumption that the maximum AH observed at any one time is equivalent to the usually observed maximum LWC (0.0002 kg m3). Such a simplification is necessary because conversion of AH to LWC is complex depending on cloud condensation nuclei and cloud physics.

Dewpoint is calculated as:

btemp=26.66082-ln(e);

Td=((btemp-sqrt((btemp**2)-223.1986))/0.0182758048)-273.15;#dewpoint, C

where

Td = Celsius

Lifting condensation level

This means that the lifting condensation level (LCL) becomes

lcl=(1/(((Newtemp-Td)/223.15)+1)**3.5)*MSLP

lcl=max((44.3308-4.94654*((lcl*100)**0.190263))*1000,0)

Where

Newtemp = ground temperature (C)

The first part of Equation 10 produces the LCL in mb and the second part in masl

MSLP = mean sea level pressure (mb)

Liquid water content is distributed rather simplistically as :

LWC=(AH/mapmaximum(AH))*0.0002

SUBMODULE : precipitation

Ground level cloud (fog) occurrence

Fog occurs where the ground altitude is greater than the LCL:

fog=scalar(Dem gt lcl)

Where

Dem = elevation (m)

Fog settling

Key assumption : That fog settling occurs under calm conditions and upwards fog turbulent diffusion is limited compared with this downward flux. Fog settling velocity is calculated according to Stokes Law based on the mean particle size for fog.

FogSettlingVel=(980*((7.5/10000)**2)*(1-0.0013))/(18*0.000185)

where 7.5 = fog droplet size in um

Forest edges

Key assumption : That forest edges are important and can be respresented as catching surfaces. That, as in the Chiquito, there is a random directionality of forest edges.

Forest is given an one sided LAI=3 and pasture LAI=2

Forest edges are calculated according to the tree fractional cover as :

forestedgefrac=-3E-05*Tree**2 + 0.0036*Tree

forestedgelenm=forestedgefrac*((CellSize*CellSize)/(25*25))*100
emergentedgelenm=(0.05*TreeFrac)*((CellSize*CellSize)/(25*25))*100
forestedgelenfacingm=(forestedgelenm/4)
emergentedgelenfacingm=(emergentedgelenm/4)

So, that the empirical equation derived from Figure 59 (Mulligan and Burke, 2005) provides the fractional forest edge length on the basis of tree fractional cover, this is converted to an actual length based on the cellsize of the grid compared with the original landsat grid. The fraction of exposed emergent trees is calculated as a 5% fractional of the area covered by tree. The division by four accounts for the fact that only one edge of a grid cell will face a wind from a particular direction.

Sedimentation surface area

Key assumption : That the whole unshaded (one sided) leaf surface area is available for sedimentation (deposition)

The surface area available for fog deposition (sedimentation) is calculated as:
ForestTrappingSfcArea=(1-(exp((-0.7*0.3*10))));#m/m*ForestLAI
PastureTrappingSfcArea=(1-(exp((-0.7*6*0.5))));#m/m*PastureLAI
DepositionFrac=(TreeFrac*ForestTrappingSfcArea*ForestLAI)+((1-TreeFrac)*PastureTrappingSfcArea*PastureLAI)

Fractional trapping areas for forest and pasture are calculated first (on the basis of leaf self shading). These are then multiplied by the fractional covers of tree and pasture for the grid cell and the available LAI.

Wind speeds modified for exposure:

Key assumption : The empirical parameters determined by Ruel (from wind tunnel studies) are representative. Exposure can be measured effectively from a DEM. Wind speeds are now modified for local wind direction dependent exposure using an approach modified from Ruel et al. (2002):

TanRainfallInclination=if(Prec gt 0 then windspd/DropTermVeloc else 0)
WindSlopeCorrectionfactor=if(Prec gt 0 then
1+Grad*TanRainfallInclination*cos(AspectDeg-WindDirDeg) else 0)
WindSlopeCorrectionfactor=max(WindSlopeCorrectionfactor,0)
Prec=Prec*WindSlopeCorrectionfactor
where:
Prec = monthly precipitation (mm)
Grad = slope gradient
AspectDeg = slope aspect (o)
WindDirDeg = wind direction (o)

Impaction fluxes

Key assumption : The windspeed reductions within forest and rough pasture measured at the FIESTA sites are generally representative

Fluxes of fog available for impaction are now calculated. The model has no spatial memory or budgeting of fog so fog passing through a forest is not necessary depleted along the flowpath – rather the model assumes that there is limitless availability of fog from the near surface atmosphere (when and where fog is present) thus no budget of atmospheric moisture is maintained. Impaction fluxes are calculated as:

WindFlux=(windspd*3600)*emergentedgelenfacingm*1.5
EmergentImpactionFlux=(LWC*WindFlux)

Wind speed at the grid scale is assumed unaffected by passing through occasional emergents. 1.5 is the average height of emergents above the surrounding canopy

(1.5m).

Finally the amount of water passing pasture is calculated using the correction for observed wind speeds at pasture heights and the height of pasture assumed to be 0.5 m. A fog inclination angle for fog inputs over forest and pasture is calculated, based on their respective wind speeds. A vertical flux is calculated as the fog settling velocity over the whole cell surface area (rather than any vertical catching surfaces). The proportion of fog inputs that are deposited rather than impacted depends upon the cosine of the fog inclination angle over grassland and forest fractions.

WindFlux=(windspd*0.5030*3600)*(1-TreeFrac)*CellSize*0.5
GrassImpactionFlux=(LWC*WindFlux)
ForestFogInclinationAngle=scalar(atan((windspd*0.6053)/FogSettlingVel))
PastureFogInclinationAngle=scalar(atan((windspd*0.5030)/FogSettlingVel))
GravityFlux=(FogSettlingVel*3600)*Celltruearea
DeposProportion=((cos(ForestFogInclinationAngle))*TreeFrac)+
cos(PastureFogInclinationAngle))*(1-TreeFrac))
ImpactionProportion=1-DeposProportion

Vegetation areas for fog interception

Key assumption : Fog impaction occurs to all non shaded leaves according to the geometrical relationships between the angle of incoming fog (wind speed dependent) and the leaf area. Impaction only occurs on windward forest edges whereas fog passes over forest canopies or falls as sedimentation on leeward (topographically sheltered) forests.

Next the actual intercepting area of vegetation for fog is calculated because this will be combined with the previously calculated fog fluxes in order to calculate the fog interception. Surface areas for interception depend upon the leaf area density of the vegetation and the angle of incoming fog relative to leaves. The equations are:

ForestTrappingSfcArea=(1-(exp((-
0.7*0.3*TreeFrac)/cos(ForestFogInclinationAngle))))
PastureTrappingSfcArea=(1-(exp((-0.7*6*(1-
TreeFrac))/cos(PastureFogInclinationAngle))))
ImpactionFrac=(AirRising*ForestTrappingSfcArea)
ImpactionFlux=(EmergentImpactionFlux+EdgeImpactionFlux+GrassImpactionFlux)

SettlingFlux=LWC*GravityFlux

First the forest trapping surface area is calculated as the self shaded area of leaves exposed to fog droplets arriving at a particular angle (for the tree fraction of the cell). Pasture trapping surface area is calculated in a similar way (also according to pasture leaf area density and observed wind speeds).
The impaction fraction is the fraction of the total potential impaction fluxes (to emergents, to edges and to grassland) that is trapped and so depends on the calculated forest trapping surface area. Importantly impaction only occurs in the model when air is rising because the model assumes that air flows close to the ground when moving uphill (usually in windward exposed) but above the ground in the leeward, more sheltered situations slopes, the parameter air rising is true for situation where upwind elevations are greater than the downwind cell.

Ratio of impaction to sedimentation
Key assumption : the balance between impaction and deposition depends upon the fluxes of water, the tendency towards lateral or vertical flow and the intercepting= areas for horizontal and vertical fluxes.

The proportional flux that will be deposited compared with that that will be impacted is calculated as:

DeposInterc=fog*(SettlingFlux*DeposProportion)*DepositionFrac;#kg/hr/cell total checked
ImpactionInterc=fog*(ImpactionFlux*ImpactionProportion)*ImpactionFrac

where the ‘flux’ is the volume of water passing by the representative surface area, the ‘frac’ is the fraction of that surface area that will intercept fog and the ‘proportion’ is the proportion of the flux that is horizontal and vertical (dependent of the balance between local horizontal wind speed and settling velocity).The parameter ‘fog’ denotes areas above the LCL for that timestep so where there is no fog there will be no fog flux. The units of FogInterc, DeposInterc and ImpactionInterc are kg/m2/hr. They are converted to mm/hr and multiplied by the cloud frequency to take account of
those periods where the site may be above the LCL but no cloud generation has occurred:

FogIntmm=(FogInterc/Celltruearea)*(CloudFreqFrac)

Monthly total fluxes are the cumulation of the four monthly diurnal; fluxes and the 144 simulation hours that they represent :

Fogtotalmm.map=Fogtotalmm.map+(FogIntmm*6*30)

SUBMODULE : evapotranspiration

Radiation receipt and correction for cloud and fog

Key assumption : The radiation reductions observed under cloud and fog at the FIESTA sites (Mulligan and Burke, 2005) are representative for other sites also.

Extra terrestrial radiation receipts are now converted to ground level radiation receipts by correction for dimming due to the presence cloud and fog using:

TransmissionLoss=if(fog eq 1 then (CloudFreqFrac*0.678)+((1-CloudFreqFrac)*-0.143) else (CloudFreqFrac*0.525)+((1-CloudFreqFrac)*-0.143))
SolarMJ=SolarMJ*(1-TransmissionLoss)

The empirical parameters for the effect of fog and cloud on radiation receipts were taken from the analysis of the hourly radiation dataset for the pasture site. In particular the measured radiation was compared with modelled extraterrestrial radiation for a the 1m pasture site pixel in which the weather station sits (Mulligan and Burke, 2005). The difference between modelled extraterrestrial and received land surface radiation by hour is a function of the transmission losses by cloud and fog. Thus these transmission losses were grouped according to those periods where the pasture site fog gauges were recording fog and those when they were not. This enabled the calculation of a mean transmission loss under cloudy conditions (no fog but Rmeas<<Rmodel) and foggy conditions (fog present and Rmeas<<Rmodel). Data were also analysed for clear conditions because the station recorded slightly lower values than the modelled values possibly because of more humid atmosphere above the station than parameterised in the atmospheric transmission component of the solar radiation model.

Net radiation

Key assumption : The solar to net radiation conversion functions measured under forest and grassland are representative for larger areas and other covers of similar density.

SolarWm=(SolarMJ*1000000)/(SecondsInMonth/2)
NetMap=((Tree/100)*(-27.9+(0.90*SolarWm)))
NetMap=NetMap+((1-(Tree/100))*(-27.5+(0.8*SolarWm)))

Again, the empirical constants for the simple linear regression of net with solar radiation for sensors above a forest and a pasture cover

Intercepted energy fractions

Key assumption : That evapotranspiration is effectively modelled at this coarse spatial and temporal scale from consideration of energy availablility and atmospheric demand for water only. Leaf area is sufficient to represent plant processes and aerodynamic resistances can safely be ignored.

For simplicity and parsimony the model does not account for stomatal behaviour but rather defines the evapotranspiration differences between forest and pasture to be a function of the radiation intercepted by the canopy since this is the driver of both transpiration and wet canopy evaporation.

ExpLAI=(1-exp(-0.7*max(1,ForestLAI)))
EtFrac=TreeFrac*ExpLAI
ExpLAI=(1-exp(-0.7*max(1,PastureLAI)))
EtFrac=EtFrac+((1-(TreeFrac+BareFrac))*ExpLAI)

Thus the overall intercepted energy for ET is the sum of energy intercepted by tree leaves and by pasture in the grid cell.

Evapo-transpiration

Key assumption : Water availability is less significant in determining evapotranspiration than energy available

Evapo-transpiration is calculated on the basis of the energy available (the net radiation received) and the surface area available for transpiration and wet canopy evaporation. Because of the time and space scales used surface, soil and wet canopy water balances were not possible so a water availability term could not be added to the model. Since available surface area (LAI) is a good surrogate for the availability of water through transpiring stomata or wet canopy evaporation, this was used here.

The equations are:

Ea=(611*exp((17.27*Newtemp)/(273.15+Newtemp)))/1000

SlopeSatCurveK=(4098*Ea)/sqr(273.15+Newtemp)

PotEvap=(SlopeSatCurveK/(SlopeSatCurveK+0.066))*NetMap

PotEvap=PotEvap*(60*60/1000000)

PotEvap=if(PotEvap gt 0 then (PotEvap/2.45) else 0)

ActEvap=if(PotEvap gt 0 then PotEvap*EtFrac else 0)

where

Newtemp = air temperature (C)

Ea = vapour pressure (KPa)

SlopeSatCurveK= slope of the saturation vapour pressure curve (KPaC)

NetMap = Net radiation receipt (W/m2)

2.45 = latent heat of vapourisation of water (MJ/kg)

Thus evaporation is calculated on the basis of available energy and atmospheric demand to give potential evaporation and this is then combined with the non self shaded surface area available for the interception of radiation/evaporation of water to give something closer to actual evaporation, which is responsive to vegetation type and cover as well as climate conditions.

SUBMODULE: water balance

Water balance calculation

Key assumption : at these time and space scales losses to canopy, soil and groundwater are much less significant than the fluxes of rainfall and evapotranspiration. Precipitation is converted to mm/hr and the budget is calculated as :

Precmmh=Prec/(24*30)

Budget=((Precmmh+FogIntmm)-ActEvap)

Appendix III: CO$TING NATURE: *VERSION 2 MODULES*

Costing Nature is aimed at incorporating ecosystem service provision and benefits information into the conservation prioritisation and planning. It focuses on water, carbon and tourism related services and on defining the magnitude and geographic pattern of these as potential services and as those realised (used) by local and global beneficiaries. Costing Nature starts by mapping individual services for water, carbon and tourism and then combines them with analysis of current pressure, future threats, biodiversity and conservation priority to produce an assessment of priority areas for conservation and careful management on the basis of all of these factors. This is done first using baseline datasets representative of the current situation. Users may then apply scenarios for climate, land use or land management change (such as for example removal of funding for a conservation area) and examine the impacts - in terms of change in ecosystem services - and implications for beneficiaries. In version 1 all outputs are expressed in relative terms as indices from 0-1 globally This is to represent priority across the the world and so that very different services and priorities can be combined in aggregate indices to which the user can then apply specific weights. The model produces a series of summary maps which combine the outputs of many of the modules described below. These maps include:

Relative conservation priority index - conservation priority of the major conservation NGOs (see module: conservation priority)

Relative biodiversity priority index - combines relative richness and relative endemism for Red-list (threatened) species for the groups mammals, amphibians and reptiles.

Relative aggregate nature conservation priority index (potential services) - this combines *total potential services* (for all services) and *total nature conservation priority* (which combines the relative conservation priority index with the biodiversity priority, current pressure, and future threat indices). Relative aggregate nature conservation priority index (potential services) is thus a measure of potential value for services coupled with nature conservation priority according to perceived value and risk of loss.

Relative aggregate nature conservation priority index (realised services) - this combines *total realised services* (for all services) and *total nature conservation priority* (which combines the relative conservation priority index with the biodiversity priority, current pressure, and future threat indices). Relative aggregate nature conservation priority index (realised services) is thus a measure of actual value of services coupled with nature conservation priority according to perceived value and risk of loss. The Co$ting Nature model consists of a number of modules as described below.

MODULE : Conservation priority

Conservation priority is considered an index of priority for conservation based on the overlap of institutional conservation priorities for major conservation NGOs. This index combines the conservation priorities of BirdLife International (Endemic Bird Areas and Important Bird Areas), WWF (Global200 priority ecoregions), Conservation International (biodiversity hotspots and KBAs), Wildlife Conservation Society (Last of the Wild). Each of these is weighted equally and the conservation priority index is essentially the number of assessments overlapping: the more overlap of individual priorities, the greater the overall conservation priority.

MODULE : Water Quantity

Water quantity is each pixel is calculated as the water balance (rainfall minus actual evapotranspiration) cumulated downstream. See Mulligan et al. (2011) for a description of the global water balance dataset.

MODULE : Water Quality

Water quality is calculated as the human footprint on water index (Mulligan, 2009) in which the potential water quality in a pixel represents the cumulation of upstream influences of point (mining, oil and gas, roads, urban areas) and non-point (pastures and croplands outside of protected areas) source potential sources of contamination. Each of these is given an equal weighting in terms of its capacity to generate contamination and for each pixel the human footprint index represents the percentage of water coming from upstream that is influenced by these point and non point sources. This is calculated as rainfall falling on these 'polluting' land areas as a percentage of total rainfall falling. Areas with extensive agriculture or urban areas will leave a significant footprint on water downstream. This may be diluted as waters coming from undisturbed areas or protected areas. The influence of small (areal) footprint sources such as mines or oil and gas will tend to diminish quickly downstream whereas large areal footprint areas will influence downstream waters for much further.

MODULE : Water Provisioning Services

Potential water provisioning services for each cell are first calculated as the sum of clean (i.e. no human footprint) water available from upstream. Realised water services are this available clean water where there are dams and in relation to population. The greater the downstream population, number of dams and actual water available, the greater the service provided. If there is plenty of water but no people or dams then there is no realised service. In this way not all water provides a direct service, only that water that is accessed and used. Where there is high available water and either a dam or high local populations the water services index will be higher. Untapped water services are considered to be the difference between potential and realised water services. All these indices are scaled from 0-1 between the minimum and the maximum for each map. The beneficiaries of realised water services are local dams, populations, irrigation projects etc.

MODULE: Carbon Services

Both carbon stocks and carbon sequestration make up the carbon services index. Potential and realised carbon services are equal since it is assumed that all carbon storage and sequestration contributes a service to global beneficiaries. Carbon stocks are calculated from the carbon stocks map of Ruesch and Gibbs (2008). Carbon sequestration is calculated from a global analysis of Mulligan (2009) based on SPOT VGHT imagery every 10 days from 1998-2008. Relative stock (t/km2) and relative sequestration (t/ha/yr) are calculated and combined in a single relative index of carbon service.

Ruesch Aaron and Holly K. Gibbs. 2008. New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000. Available online from the Carbon Dioxide Information Analysis Center [http://cdiac.ornl.gov] Oak Ridge National Laboratory Oak Ridge Tennessee.

Mulligan, M. (2009) Global mean dry matter productivity based on SPOT-VGT (1998-2008). http://www.ambiotek.com/dmp

MODULE : Biodiversity

Biodiversity is not a service *per se* but is important culturally, aesthetically and as a potential supporting framework for ecosystems and the services that they provide. Biodiversity loss is therefore to be avoided wherever possible. Two elements of biodiversity are considered as important for conservation priority: (a) species richness (number) of threatened species and (b) endemism or range size rarity of threatened species. The data available makes these calculation possible for mammals, amphibians and reptiles. The Costing Nature biodiversity index thus combined relative species richness of threatened mammals, amphibians and reptiles and relative range size rarity using the C-value (Barthlott et al., 2001). Species richness and endemism are equally weighted in the combined index.

Barthlott, W., V. Schmit-Neuerburg, J. Nieder, and S. Engwald (2001). Diversity and abundance of vascular epiphytes: a comparison of secondary vegetation and primary montane rain forest in the Venezuelan Andes. Plant Ecology 152: 145–156.

MODULE : Recreation

Potential recreational services are calculated according to the potential natural attraction of an area (defined according to its conservation priority index), with its accessibility to populations. Areas that are high conservation priority and accessible to significant populations and urban centres receive higher potential recreational services values (for both local and international tourism) than low conservation priority areas or areas that are less easily accessible. Urban areas are masked out of the analysis since the focus here is on nature tourism not on urban tourism. Potential recreational value is calculated as cumulated population weighted accessibility from each urban centre outwards. Accessibility is defined using the agglomeration index of Uchida and Nelson (2009). This is calculated only for non-urban and sub-urban areas and is multiplied by the conservation priority index. Where accessibility or population or conservation priority is high this will increase the potential recreation index. As always the index is expressed 0-1.

Realised recreational services will only be a fraction of the potential services because many potentially good recreational sites will not be realised because of infrastructural, market, development and political or security barriers to tourism. We produce an index of realised recreational services using the online geo-referenced photographic database of Panoramio which contains more than 5 million geo-referenced photographs. Photographs uploaded to this database are considered to represent evidence of high value urban-rural or international tourism having taken place. The Panoramio database has been 'scraped' for the number of geo-referenced photos by different users (i.e. the number of tourists having taken photos) per 25km. These are interpolated to the standard simterra grids at 1km or 1 hectare resolution and masked to remove photographs in urban areas. Finally a conversion to relative index (0-1) indicates the areas with lowest and highest realised tourism services.

Uchida, H. and Nelson, A. (2009) Agglomeration Index: Towards a New Measure of Urban Concentration. Background paper for the World Bank's World Development Report.

MODULE : Threats and pressures

In addition to value for ecosystem services and biodiversity, one has to consider risk of loss in any conservation prioritisation. Risk of loss/damage can be assessed from measures of current human pressure on the system and of future threat. The index of current pressure is given as the combination of relative population, relative fire frequency, relative grazing intensity, relative agricultural intensity, relative dam density and relative infrastructural density. Relative population is calculated on the basis of population density. Relative fire frequency is based on an analysis of the mean burn frequency from 2001-2010 from the MODIS burnt area product (Mulligan, 2010). Grazing intensity is calculated according to head of cattle for managed grazing and wildland grazing after Wint and Robinson (2007). Agricultural intensity combines the fractions of cropland and pasture in each pixel. Pressure from dams is calculated as the cumulative upstream number of dams using the Global Dams Database (Mulligan et al, 2009). Infrastructural pressure is calculated from the location of dams, mines, oil and gas, roads and urban infrastructure. Relative pressure is again scaled from 0-1. Threats are distinct from pressures because pressure refers to current pressure whereas threat is the potential to increase pressure into the future. The costing nature relative threat index combines threats of land use change, climate change and infrastructural change. All threats are assumed to be related to accessibility to populations through the roads network. The threat of deforestation is assumed to scale with proximity to existing deforestation fronts according to MODIS VCFchange, threats from infrastructure are assumed to scale with projected change in GDP and threats from population to scale with projected population change. Threats from climate change are assumed to scale with 17GCM ensemble projected IPCC AR4 A2a temperature and precipitation change to the 2050s. Finally remote threats such as mining and oil and gas (that may be distant from populations, urban areas and roads) are assumed to be greater in proximity to existing night time lights. All of these threats are given equal weight and scaled from 0-1 in the final threats map.

Mulligan, M. (2010) Fire-burn frequency dataset based on MODIS burnt area product. http://www.ambiotek.com/fire

Mulligan, M. Saenz-Cruz , L., van Soesbergen, A., Smith,V.T. and Zurita,L (2009) Global dams database and geowiki. Version 1. http://www.ambiotek.com/dams. Version 1. http://www.ambiotek.com/dams

Wint,G.R.W. and T.P. Robinson. (2007). Gridded livestock of the world 2007. FAO, Rome, 131 pp.

MODULE: Vulnerability to hazards

Ecosystems have a role to play in the m of natural hazards. In Co$ting Nature, we first calculate the environmental potential for hazards as an inditigationex varying from 0 to 1 globally. We then calculate human socio-economic exposure to this hazard and combine this with a measure of vulnerability to hazard in order to calculate risk where risk is the product of hazard exposure and vulnerability. Potential hazard mitigation services provided by nature for coastal inundation, floods, regulation services (e.g. drought) and landslides/soil erosion. These are then combined with risk to calculate realised hazard mitigation services as the minimum of the risk and potential hazard mitigation services indices.

We calculate an index of potential hazards taking into account cyclones, coastal inundation, landslides and soil erosion, floods and droughts. The potential cyclone hazard is calculated as the relative cyclone hazard frequency of Dilley et al. (2005). Potential flood hazard is calculated as proportional to the available water in each pixel (downstream cumulated rainfall minus actual evapotranspiration). Coastal inundation hazard is considered to be inversely proportional to elevation in the range 0-30 masl and in coastal areas (that is to say within 2000m of the coast). The coastal inundation hazard index (0-1) is comprised of sea level rise hazard (assumed to be uniform globally, global relative Tsunami hazard (mapped by Mulligan, 2011 based on NGDC data) and global relative cyclone frequency as above. Potential hazards from landslides are assumed to scale with relative global mean upstream slope gradient. Hazard potential is then the mean of the cyclone hazard index, coastal inundation hazard index, landslide hazard index and flood hazard index.

Exposure to hazards is considered to scale with the relative human population, relative infrastructure, relative agriculture and relative GDP indices. Hazard exposure is then the product of hazard potential and hazard exposure. Vulnerability is assumed to scale inversely with combined GDP and infrastructure such that high GDP and infrastructure leads to lower vulnerability (even though they may also contribute to higher exposure). Risk is then the product of exposure and vulnerability.

Ecosystems provide a range of potential hazard mitigation services. These can derive from ecosystem processes *in situ* or elsewhere (e.g. upstream). The hazard mitigation services currently considered are landslide/erosion control, coastal protection, flood storage/mitigation, flow regulation). Landslide/erosion control is considered to be provided by the presence of vegetation, especially trees. Therefore the erosion control service is assumed to scale with the proportion of upstream land that is tree-covered. This tree cover index is also assumed to control the flow regulation service at a point. Flood control is assumed to be provided by water bodies, wetlands and floodplains, all of which provide storage capacity for flood waters. Thus the flood protection services provided to a particular point are assumed to scale with the upstream cover of water bodies, wetlands and floodplains. Coastal protection is assumed to be provided is coastal (within 2000m of the coast and from 0-30m above mean sea level) by mangroves and by wetlands in those areas. Total potential hazard mitigation services is thus the sum of coastal protection, flood protection, flow regulation and soil erosion/landslide control services. Of course not all potential hazard mitigation services are realised since in many places the potential hazard or the actual risk are low. This the realised hazard mitigation services are calculates as the minimum of the potential hazard mitigation services and the actual risk.

National Geophysical Data Center / World Data Center (NGDC/WDC) Historical Tsunami Database, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)

Dilley et al (2005) Natural Disaster Hotspots: A Global Risk Analysis. Version 1.0. Disaster Risk Management Series, No 5. World Bank, Washington DC

MODULE: Beneficiaries

Costing Nature provides spatially explicit assessments of realised ecosystem services according to the distribution of population, infrastructure and risk and thus inherently identifies a set of beneficiaries. Costing Nature also provides maps for those services realised by local beneficiaries (water provisioning, tourism, hazard mitigation) and those realised by global beneficiaries (carbon storage and sequestration for climate change mitigation).

ALTERNATIVES

Costing Nature is a simple, data-based phenomenological model for ecosystem services, not a fully parameterised, physically-based model. Therefore in applying scenarios for land use, land management and climate change we use techniques based on the identification of analogous areas to assign multi-ecosystem service values to areas that have undergone change. Analogous zones for land cover and use change are identified as follows: mean annual temperature and mean annual precipitation are zoned into 10 classes each which, when combined, can produce as many as 100 class combinations. Within each of these temperature and precipitation zones we identify pixels that have in the baseline the tree and herb cover values (within 5%) that are assigned in the scenario. The mean value in these areas for each service affected by land use and cover change is assigned to changed pixels in the respective zone. In this way the value of say carbon storage in an area converted from tree cover to pasture is assigned by identifying the mean value of all pasture pixels in the same climate zone (according to temperature and precipitation). This value is then assigned to all changed pixels.